WELDING HANDBOOK

THIRD EDITION

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Prepared under the direction of
the Welding Handbook Committee

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PREFACE

THE WELDING HANDBOOK is recognized throughout the world as a source of authoritative information. In preparing the Third Edition, no effort was spared to maintain the reputation established by the earlier editions. The Third Edition of the WELDING HANDBOOK contains information on welding in all its aspects, based on recognized practices in industry at the time of its issuance.

To make it more useful the arrangement of information in the Third Edition differs from that in the 1942 Edition based on suggestions received from HANDBOOK users in the course of a nationwide survey; the following brief remarks on these differences may assist the reader in securing maximum benefit from this HANDBOOK.

The individual chapters are arranged in groups, principally by processes, materials and applications. The material contained in each chapter in a given group is arranged in the same general order and under the same major headings in so far as possible. Thus a reader who has acquired familiarity with the contents of one chapter may expect to find the same types of information in the same relative locations in any other chapter within the same group.

Because of the many new welding developments and applications since 1942, it was necessary to include a considerable amount of information that was not in previous editions of the HANDBOOK. To accomplish this without making the book too large for frequent use, the text is set in two columns instead of one, and in so far as possible, data are given in tables instead of in the text; these tables make the HANDBOOK more useful for ready reference. Space is further saved by including cross references in each chapter to related information in other chapters thus avoiding repetition. Ease of finding information is further enhanced by an enlarged index.

Recognizing the impossibility of including all information on every subject within the limits of a single book, a bibliography is included at the end of each chapter listing the more important technical articles and books as well as applicable codes, standards and specifications published on the subject of that chapter.

A complete chapter is devoted to general engineering tables, which were selected to satisfy the need for such data in both the shop and the office.

Even with all of the foregoing changes much of the information contained in the Third Edition was drawn from the 1942 Edition, with revisions made as necessary to bring it up to date. Although the authors who contributed to the 1942 Edition are not listed, their indirect contributions to the Third Edition are gratefully acknowledged.

It would have been impossible to prepare the Third Edition without the generous contributions of time and effort of the members of the chapter committees, whose names are shown at the beginnings of the chapters and in the Index of Authors at the back of the HANDBOOK. Appreciation is also expressed to the companies with

which these members are affiliated for their understanding of the need for these contributions and the tolerance with which they accepted interruptions in company business so that this HANDBOOK could be published

Particular appreciation is extended to the members of the WELDING HANDBOOK Committee who not only planned each step so that the Third Edition would be as useful as possible, but who read each chapter carefully and through many revisions.

Very special acknowledgment is due to Mr. H. C. Boardman, for whom, as chairman of the WELDING HANDBOOK Committee, preparation of the Third Edition became a responsibility never to be forgotten, and who by his tireless and conscientious effort inspired all other committee members.

While this HANDBOOK is intended primarily to serve as a source of information for engineers in the design, fabrication and inspection of welded construction it should prove useful to anyone seeking information on welding; the text is sufficiently extensive to make it useful as an engineering textbook.

The Third Edition of the WELDING HANDBOOK is presented as a tribute to the members of the AMERICAN WELDING SOCIETY and the welding industry which they represent. It is dedicated to meeting their needs with the hope that it will serve this purpose well.

SIMON A. GREENBERG, *Editor*

January 1950

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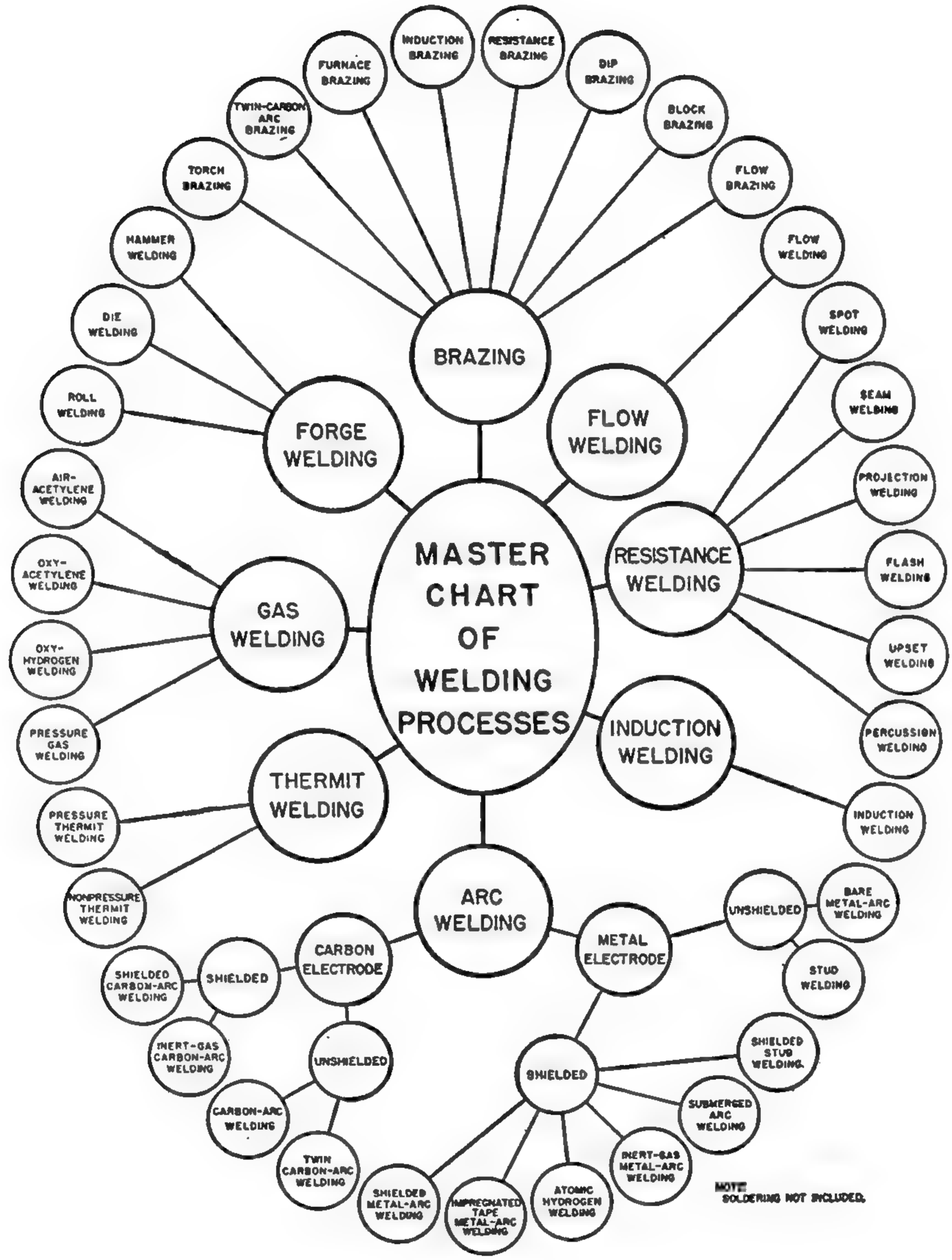
MASTER CHART OF WELDING PROCESSES
BRAZING
TORCH BRAZING
TWIN-CARBON ARC BRAZING
FURNACE BRAZING
INDUCTION BRAZING
RESISTANCE BRAZING
DIP BRAZING
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ATOMIC HYDROGEN WELDING
IMPREGNATED TAPE METAL-ARC WELDING
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NOTE
SOLDERING NOT INCLUDED.

CHAPTER 1

STANDARD WELDING TERMS AND THEIR DEFINITIONS*†

A

Actual Throat: See Throat of a Fillet Weld.

Air-Acetylene Welding: A gas-welding process wherein coalescence is produced by heating with a gas flame or flames obtained from the combustion of acetylene with air, without the application of pressure and with or without the use of filler metal.

All-Weld-Metal Test Specimen: A test specimen wherein the portion being tested is composed wholly of weld metal.

Angle of Bevel: See Bevel Angle.

Arc Brazing: See Twin-Carbon Arc Brazing.

Arc Cutting: A group of cutting processes wherein the severing of metals is effected by melting with the heat of an arc between an electrode and the base metal. See Carbon-Arc Cutting and Metal-Arc Cutting. See also Oxy-Arc Cutting.

Arc Oxygen Cutting: See Oxy-Arc Cutting.

Arc Voltage: The voltage across the welding arc.

Arc Welding: A group of welding processes wherein coalescence is produced by heating with an electric arc or arcs, with or without the application of pressure and with or without the use of filler metal.

Arm: See Horn.

As-Welded: The condition of weld metal, welded joints and weldments after welding prior to any subsequent thermal or mechanical treatment.

Atomic Hydrogen Welding: An arc-welding process wherein coalescence is produced by heating with an electric arc maintained between two metal electrodes in an atmosphere of hydrogen. Shielding is obtained from the hydrogen. Pressure may or may not be used and filler metal may or may not be used.

Automatic Gas Cutting: See Automatic Oxygen Cutting.

Automatic Oxygen Cutting: Oxygen cutting with equipment which performs the cutting operation without constant observation and adjustment of the controls by an operator. The equipment may or may not perform loading and unloading of the work. See Machine Oxygen Cutting.

Automatic Welding: Welding with equipment which performs the entire welding operation without constant observation and adjustment of the controls by an operator. The equipment may or may not perform the loading and unloading of the work. See Machine Welding.

Axis of a Weld: A line through the length of a weld, perpendicular to the cross-section at its center of gravity. See Figs. 1 and 2.

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* The Master Chart and Process Charts, which classify the welding processes and show their differences and similarities, will be helpful in understanding some of these definitions. They are too large for inclusion in this standard and are available separately.

† Prepared by the AWS Committee on Definitions and Chart.

B

Back Bead: See Back Weld.

Backfire: The momentary recession of the flame into the torch tip followed by immediate reappearance or complete extinguishment of the flame.

Backhand Welding: A gas-welding technique wherein the flame is directed opposite to the progress of welding. See Fig. 4.

Backing: Material (metal, weld metal, asbestos, carbon, granular flux, etc.) backing up the joint during welding to facilitate obtaining a sound weld at the root.

Backing Bead: See Backing Weld.

Backing Pass: A pass made to deposit a backing weld.

Backing Ring: Backing in the form of a ring generally used in the welding of piping.

Backing Strap: See Backing Strip.

Backing Strip: Backing in the form of a strip.

Backing Weld: Backing in the form of a weld. See Fig. 6.

Back Pass: A pass made to deposit a back weld.

Back Weld: A weld deposited at the back of a single-groove weld. See Fig. 7.

Backstep Sequence: A longitudinal sequence wherein the weld bead increments are deposited in the direction opposite to the progress of welding the joint. See Block Sequence, Longitudinal Sequence, etc. See Fig. 8.

Backup: In flash and upset welding, a locator, used to transmit all or a portion of the upsetting force to the work pieces.

Bare Electrode: A filler-metal electrode, used in arc welding, consisting of a metal wire with no coating other than that incidental to the drawing of the wire.

Bare Metal-Arc Welding: An arc-welding process wherein coalescence is produced by heating with an electric arc between a bare or lightly-coated metal electrode and the work and no shielding is used. Pressure is not used and filler metal is obtained from the electrode.

Base Metal: The metal to be welded or cut.

Base-Metal Test Specimen: A test specimen composed wholly of base metal.

Beading: See String Beading and Weave Beading.

Bead Weld: A type of weld composed of one or more string or weave beads deposited on an unbroken surface. See Fig. 13.

Bevel: A type of edge preparation.

Bevel Angle: The angle formed between the prepared edge of a member and a plane perpendicular to the surface of the member. See Fig. 18.

Beveling: A type of chamfering.

Blacksmith Welding: See Forge Welding.

Block Brazing: A brazing process wherein coalescence is produced by the heat obtained from heated blocks applied to the parts to be joined and by using a nonferrous filler metal having a melting point above 800° F. but below that of the base metals. The filler metal is distributed in the joint by capillary attraction.

Block Sequence: A combined longitudinal and build-up sequence for a continuous multiple-pass weld wherein separated lengths are com-

pletely or partially built up in cross-section before intervening lengths are deposited. See Backstep Sequence, Longitudinal Sequence, etc. See Fig. 9.

Blowhole: See Gas Pocket.

Blowpipe: See Welding Torch or Cutting Torch.

Bond: The junction of the weld metal and the base metal, or the junction of the base metal parts when weld metal is not present. See Fig. 21.

Bottle: See Cylinder.

Boxing: The operation of continuing a fillet weld around a corner of a member as an extension of the principal weld. See Fig. 22.

Braze: A weld wherein coalescence is produced by heating to suitable temperatures above 800° F. and by using a nonferrous filler metal, having a melting point below that of the base metals. The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction.

Braze Welding: A method of welding whereby a groove, fillet, plug or slot weld is made using a nonferrous filler metal, having a melting point below that of the base metals but above 800° F. The filler metal is not distributed in the joint by capillary attraction. (Bronze Welding, formerly used, is a misnomer for this term.)

Brazed Joint: A union of two or more members produced by the application of a brazing process.

Brazing (Noun): A group of welding processes wherein coalescence is produced by heating to suitable temperatures above 800° F. and by using a nonferrous filler metal, having a melting point below that of the base metals. The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction.

Brazing Technique: See Welding Technique.

Build-Up Sequence: The order in which the weld beads of a multiple-pass weld are deposited with respect to the cross-section of the joint. Block-Sequence, Longitudinal Sequence, etc. See Fig. 10.

Burner: See Oxygen Cutter.

Burning In: See Flow Welding.

Butt Joint: A joint between two members lying approximately in the same plane. See Fig. 17.

Butt Weld: A weld in a butt joint.

Button: In the destructive testing of spot-, seam- and projection-welded specimens, that part of a weld, including all or part of the nugget, which tears out.

C

Capillary Attraction: The phenomenon by which adhesion between the molten filler metal and the base metals, together with surface tension of the molten filler metal, distribute the filler metal between the properly fitted surfaces of the joint to be brazed.

Carbon-Arc Cutting: An arc-cutting process wherein the severing of metals is effected by melting with the heat of an arc between a carbon electrode and the base metal.

Carbon-Arc Welding: An arc-welding process wherein coalescence is produced by heating with an electric arc between a carbon electrode and

the work and no shielding is used. Pressure may or may not be used and filler metal may or may not be used.

Carbon Electrode: A non-filler-metal electrode, used in arc welding, consisting of a carbon or graphite rod.

Carbon-Electrode Arc Welding: A group of arc-welding processes wherein carbon electrodes are used. See Shielded Carbon-Arc Welding, Inert-Gas Carbon-Arc Welding, Carbon-Arc Welding and Twin-Carbon Arc Welding.

Carbonizing Flame: See Reducing Flame.

Carburizing Flame: See Reducing Flame.

Cascade Sequence: A combined longitudinal and build-up sequence wherein weld beads are deposited in overlapping layers. (In manual shielded metal-electrode arc-welding a backstep sequence is normally used.) See Block Sequence, Build-Up Sequence, Longitudinal Sequence, etc. See Fig. 11.

Chain Intermittent Fillet Welding: Two lines of intermittent fillet welding on a joint wherein the fillet weld increments in one line are approximately opposite to those in the other line. See Fig. 23.

Chamfer: See Edge Preparation.

Chamfering: The preparation of a contour, other than for a square groove weld, on the edge of a member for welding.

Chill Ring: See Backing Ring.

Circular Seam Welding: See Transverse Seam Welding.

Circumferential Seam Welding: See Transverse Seam Welding.

Coated Electrode: See Covered Electrode and Lightly-Coated Electrode.

Collar: The reinforcing metal of a non-pressure thermit weld.

Commutator-Controlled Welding: The making of a number of spot or projection welds wherein several electrodes, in simultaneous contact with the work, progressively function under the control of an electrical commutating device.

Complete Fusion: Fusion which has occurred over the entire base-metal surfaces exposed for welding. See Fig. 26.

Complete Joint Penetration: Joint penetration which extends completely through the joint. See Joint Penetration. See Fig. 29.

Complete Penetration: See Complete Joint Penetration.

Composite Electrode: A filler-metal electrode, used in arc welding, consisting of more than one metal component combined mechanically. It may or may not include materials which protect the molten metal from the atmosphere, improve the properties of the weld metal or stabilize the arc.

Composite Joint: A joint wherein welding is used in conjunction with a mechanical joining process.

Concave Fillet Weld: A fillet weld having a concave face. See Fig. 31.

Concavity: The maximum distance from the face of a concave fillet weld perpendicular to a line joining the toes. See Fig. 31.

Concurrent Heating: The application of supplemental heat to a structure during a welding or cutting operation.

Cone: The conical part of a gas flame next to the orifice of the tip. See Figs. 38, 39 and 40.

Continuous Sequence: A longitudinal sequence wherein each pass is

made continuously from one end of the joint to the other. See Back-step Sequence, Longitudinal Sequence, etc.

Continuous Weld: A weld which extends without interruption for its entire length.

Convex Fillet Weld: A fillet weld having a convex face. See Fig. 32.

Convexity: The maximum distance from the face of a convex fillet weld perpendicular to a line joining the toes. See Fig. 32.

Cool Time: In multiple-impulse welding and seam welding, the time interval between successive heat times. See Figs. 53, 54 and 55.

Corner Joint: A joint between two members located approximately at right angles to each other in the form of an *L*. See Fig. 17.

Corona: The area sometimes surrounding the nugget of a spot weld at the faying surfaces, which provides a degree of bonding.

Cover Glass: A clear glass used in goggles, hand shields and helmets to protect the filter glass from spattering material.

Covered Electrode: A filler-metal electrode, used in arc welding, consisting of a metal core wire with a relatively thick covering which provides protection for the molten metal from the atmosphere, improves the properties of the weld metal and stabilizes the arc.

Crater: A depression at the termination of a weld bead.

Crater Crack: A crack in the crater of a weld bead.

Cross Wire Weld: A projection weld made between crossed wires or bars.

Current Regulator: An automatic electrical control device for maintaining a constant current in the primary of the welding transformer.

Cutting Attachment: A device which is attached to a gas-welding torch to convert it into an oxygen-cutting torch.

Cutting Nozzle: See Cutting Tip.

Cutting Tip: That part of an oxygen-cutting torch from which the gases issue.

Cutting Torch: A device used in oxygen cutting for controlling and directing the gases used for preheating and the oxygen used for cutting the metal.

Cylinder: A portable cylindrical container used for transportation and storage of a compressed gas.

Cylinder Manifold: See Manifold.

D

Deposit Sequence: See Deposition Sequence.

Deposited Metal: Filler metal that has been added during a welding operation.

Deposition Efficiency: The ratio of the weight of deposited metal to the net weight of electrodes consumed, exclusive of stubs.

Deposition Rate: The weight of metal deposited in a unit of time.

Deposition Sequence: The order in which the increments of weld metal are deposited. See Longitudinal Sequence and Build-Up Sequence.

Depth of Fusion: The distance that fusion extends into the base metal from the surface melted during welding. See Fig. 25.

Die:

Resistance Welding.—A member usually shaped to the work contour to clamp the parts being welded and conduct the welding current.

Forge Welding.—A device used in forge welding primarily to form the work while hot and apply the necessary pressure.

Die Welding: A forge-welding process wherein coalescence is produced by heating in a furnace and by applying pressure by means of dies.

Dip Brazing: A brazing process wherein coalescence is produced by heating in a molten chemical or metal bath and by using a nonferrous filler metal, having a melting point above 800° F. but below that of the base metals. The filler metal is distributed in the joint by capillary attraction. When a metal bath is used, the bath provides the filler metal.

Double-Bevel Groove Weld: A type of groove weld. See Fig. 12.

Double-J Groove Weld: A type of groove weld. See Fig. 12.

Double-U Groove Weld: A type of groove weld. See Fig. 12.

Double-Vee Groove Weld: A type of groove weld. See Fig. 12.

Downhand: See Flat Position.

Drag: The distance between the point of exit of the cutting oxygen stream and the projection, on the exit surface, of the point of entrance. See Fig. 33.

Dynamic Electrode Force: See Electrode Force.

E

Edge Joint: A joint between the edges of two or more parallel or nearly parallel members. See Fig. 17.

Edge Preparation: The contour prepared on the edge of a member for welding.

Effective Length of Weld: The length of weld throughout which the correctly proportioned cross-section exists.

Electrode:

Arc Welding.—See Bare Electrode, Carbon Electrode, Composite Electrode, Covered Electrode, Lightly-Coated Electrode, Metal Electrode and Tungsten Electrode.

Resistance Welding.—The part or parts of a resistance-welding machine through which the welding current and, in most cases, pressure are applied directly to the work. The electrode may be in the form of a rotating wheel, rotating roll, bar, cylinder, plate, clamp, chuck or modification thereof.

Electrode Force:

Dynamic.—In spot, seam and projection welding, the force (pounds) between the electrodes during the actual welding cycle.

Theoretical.—In spot, seam and projection welding, the force, neglecting friction and inertia, available at the electrodes of a resistance welding machine by virtue of the initial force application and the theoretical mechanical advantage of the system.

Static.—In spot, seam and projection welding, the force between the electrodes under welding conditions, but with no current flowing and no movement in the welding machine.

Electrode Holder: A device used for mechanically holding the electrode and conducting current to it.

Electrode Lead: The electrical conductor between the source of arc-welding current and the electrode holder. See Figs. 34 and 35.

Electrode Skid: During spot, seam or projection welding, the sliding of an electrode along the surface of the work.
Electronic Heat Control: A device for adjusting the heating value (rms value) of the current in making a resistance weld by controlling the ignition or firing of the tubes in an electronic contactor. The flow of current is initiated each half-cycle at an adjustable time with respect to the zero point on the voltage wave.
End Return: See Boxing.

F

Face of Weld: The exposed surface of a weld, made by an arc- or gas-welding process, on the side from which welding was done. See Fig. 20.
Face Shield: See Hand Shield.
Faying Surface: That surface of a member which is in contact with another member to which it is to be joined.
Filler Metal: Metal to be added in making a weld.
Fillet Weld: A weld of approximately triangular cross-section joining two surfaces approximately at right angles to each other in a lap joint, tee joint or corner joint. See Figs. 31 and 32.
Fillet Weld Size: See Size of Weld.
Filter Glass: A glass, usually colored, used in goggles, helmets and hand shields to exclude harmful light rays.
Flame Cutting: See Oxygen Cutting.
Flame Gouging: See Oxygen Gouging.
Flash: The molten metal which is expelled, or which is squeezed out by the application of pressure, and solidifies around the weld.
Flashback: A recession of the flame into or back of the mixing chamber of the torch.
Flash-Butt Welding: See Flash Welding.
Flashing Time: In flash welding the time during which the flashing action is taking place. See Fig. 56.
Flash-Off Time: See Flashing Time.
Flash Weld: A weld made by flash welding. See Fig. 16.
Flash Welding: A resistance-welding process wherein coalescence is produced, simultaneously over the entire area of abutting surfaces, by the heat obtained from resistance to the flow of electric current between the two surfaces, and by the application of pressure after heating is substantially completed. Flashing and upsetting are accompanied by expulsion of metal from the joint.
Flat Position: The position of welding wherein welding is performed from the upper side of the joint and the face of the weld is approximately horizontal. See Figs. 1 and 2.
Flow Brazing: A brazing process wherein coalescence is produced by heating with molten nonferrous filler metal poured over the joint until brazing temperature is attained. The filler metal has a melting point above 800° F. but below that of the base metals and is distributed in the joint by capillary attraction.
Flow Welding: A welding process wherein coalescence is produced by heating with molten filler metal, poured over the surfaces to be welded until the welding temperature is attained and until the required filler

metal has been added. The filler metal is not distributed in the joint by capillary attraction. (Burning In, formerly used, is a misnomer for this term.)

Flux: Fusible material used in welding or oxygen-cutting to dissolve and facilitate removal of oxides and other undesirable substances.

Flux-Oxygen Cutting: An oxygen-cutting process wherein severing of metals is effected by using a flux to facilitate the cutting.

Forehand Welding: A gas-welding technique wherein the flame is directed toward the progress of welding. See Fig. 5.

Forge-Delay Time: In spot and projection welding, the time between the beginning of weld time, or weld interval, and the time when the electrode force first reaches the specified pressure for forging. See Fig. 54.

Forge Welding: A group of welding processes wherein coalescence is produced by heating in a forge or other furnace and by applying pressure or blows.

Full Fillet Weld: A fillet weld whose size is equal to the thickness of the thinner member joined.

Furnace Brazing: A brazing process wherein coalescence is produced by the heat obtained from a furnace and by using a nonferrous filler metal, having a melting point above 800° F. but below that of the base metals. The filler metal is distributed in the joint by capillary attraction.

Fused Zone: See Fusion Zone, Nugget and Bond.

Fusion: The melting together of filler metal and base metal, or of base metal only, which results in coalescence. See Depth of Fusion.

Fusion Zone: The area of base metal melted as determined on the cross-section of a weld. See Fig. 21.

G

Gas Brazing: See Torch Brazing.

Gas Cutter: See Oxygen Cutter.

Gas Cutting: See Oxygen Cutting.

Gas Gouging: See Oxygen Gouging.

Gas Pocket: A weld cavity caused by entrapped gas.

Gas Regulator: See Regulator.

Gas Torch: See Welding Torch and Cutting Torch.

Gas Welding: A group of welding processes wherein coalescence is produced by heating with a gas flame or flames, with or without the application of pressure, and with or without the use of filler metal.

Goggles: See Welding Goggles.

Groove: The opening provided for a groove weld.

Groove Angle: The total included angle of the groove between parts to be joined by a groove weld. See Fig. 18.

Groove Face: That surface of a member included in the groove. See Fig. 19.

Groove Radius: The radius of a J- or U-Groove. See Fig. 18.

Groove Weld: A weld made in the groove between two members to be joined. The standard types of groove welds (Fig. 12) are as follows.

Square Groove Weld
Single-Vee Groove Weld
Single-Bevel Groove Weld

Single-U Groove Weld
Single-J Groove Weld
Double-Vee Groove Weld
Double-Bevel Groove Weld
Double-U Groove Weld
Double-J Groove Weld

Ground Connection: The connection of the work lead to the work. See Figs. 34 and 35

Ground Lead: See Work Lead.

H

Hammer Welding: A forge-welding process wherein coalescence is produced by heating in a forge or other furnace and by applying pressure by means of hammer blows.

Hand Shield: A protective device, used in arc welding, for shielding the face and neck. A hand shield is equipped with a suitable filter glass and is designed to be held by hand.

Hard Surfacing: See Surfacing.

Heat-Affected Zone: That portion of the base metal which has not been melted, but whose mechanical properties or microstructures have been altered by the heat of welding or cutting. See Fig. 41.

Heat Time: In multiple impulse welding or seam welding, the time that the current flows during any one impulse. See Figs. 53, 54 and 55.

Heating Gate: The opening in a thermit mold through which the parts to be welded are preheated.

Helmet: A protective device, used in arc welding, for shielding the face and neck. A helmet is equipped with a suitable filter glass and is designed to be worn on the head.

Hold Time:

1. In spot and projection welding, the time during which force is applied at the point of welding after the last impulse of current ceases to flow. See Figs. 53 and 54.
2. In seam, flash and upset welding the time during which force is applied to the work after current ceases to flow. See Figs. 55, 56 and 57.

Horizontal Fixed Position:

Pipe Welding.—The position of a pipe joint wherein the axis of the pipe is approximately horizontal and the pipe is not rotated during welding. See Fig. 3.

Horizontal Position:

Fillet Weld.—The position of welding wherein welding is performed on the upper side of an approximately horizontal surface and against an approximately vertical surface. See Fig. 2.

Groove Weld.—The position of welding wherein the axis of the weld lies in an approximately horizontal plane and the face of the weld lies in an approximately vertical plane. See Fig. 1.

Horizontal Rolled Position:

Pipe Welding.—The position of a pipe joint wherein welding is performed in the flat position by rotating the pipe. See Fig. 3.

Horn: In resistance welding, a beam or arm, extending from the frame

of a welding machine which transmits the electrode force and usually conducts the welding current.

Horn Spacing: In a resistance-welding machine, the unobstructed work clearance between horns or platens at right angles to the throat depth. This distance is measured with the horns parallel and horizontal at the end of the downstroke.

Hydrogen Brazing: A method of furnace brazing in a hydrogen atmosphere.

Hydromatic Welding: See Pressure-Controlled Welding.

I

Impregnated-Tape Metal-Arc Welding: An arc-welding process wherein coalescence is produced by heating with an electric arc between a metal electrode and the work. Shielding is obtained from decomposition of an impregnated tape wrapped around the electrode as it is fed to the arc. Pressure is not used and filler metal is obtained from the electrode.

Inadequate Joint Penetration: Joint penetration which is less than that specified.

Included Angle: See Groove Angle.

Incomplete Fusion: Fusion which is less than complete. See Fig. 27.

Indentation: In a spot, seam or projection weld, the depression on the exterior surface or surfaces of the base metal.

Induction Brazing: A brazing process wherein coalescence is produced by the heat obtained from resistance of the work to the flow of induced electric current and by using a nonferrous filler metal, having a melting point above 800° F. but below that of the base metals. The filler metal is distributed in the joint by capillary attraction.

Induction Welding: A welding process wherein coalescence is produced by the heat obtained from resistance of the work to the flow of induced electric current, with or without the application of pressure.

Inert-Gas Carbon-Arc Welding: An arc-welding process wherein coalescence is produced by heating with an electric arc between a carbon electrode and the work. Shielding is obtained from an inert gas such as helium or argon. Pressure may or may not be used and filler metal may or may not be used.

Inert-Gas Metal-Arc Welding: An arc-welding process wherein coalescence is produced by heating with an electric arc between a metal electrode and the work. Shielding is obtained from an inert gas such as helium or argon. Pressure may or may not be used and filler metal may or may not be used.

Intermittent Weld: See Intermittent Welding.

Intermittent Welding: Welding wherein the continuity is broken by recurring unwelded spaces. See Figs. 23 and 24.

Interpass Temperature: In a multiple-pass weld, the lowest temperature of the deposited weld metal before the next pass is started.

J

Joint Brazing Procedure: The materials, detailed methods and practices employed in the brazing of a particular joint.

Joint Design: The joint geometry together with the required dimensions of the welded joint.
Joint Geometry: The shape and dimensions of a joint in cross-section prior to welding.
Joint Penetration: The minimum depth a groove weld extends from its face into a joint, exclusive of reinforcement. See Fig. 28.
Joint (Unwelded): The location where two or more members are to be joined by welding.
Joint (Welded): See Welded Joint.
Joint Welding Procedure: The materials, detailed methods and practices employed in the welding of a particular joint.
Joint Welding Sequence: See Build-Up Sequence.

K

Kerf: The space from which metal has been removed by a cutting process. See Fig. 33.

L

Lack of Fusion: See Incomplete Fusion.
Lack of Joint Penetration: See Inadequate Joint Penetration.
Lap Joint: A joint between two overlapping members. See Fig. 17.
Layer: A stratum of weld metal, consisting of one or more weld beads. See Fig. 36.
Lead Burning: A misnomer for the welding of lead.
Leg of a Fillet Weld: The distance from the root of the joint to the toe of the fillet weld. See Figs. 31 and 32.
Lightly Coated Electrode: A filler-metal electrode, used in arc welding, consisting of a metal wire with a light coating applied subsequent to the drawing operation, primarily for stabilizing the arc.
Local Preheating: Preheating a specific portion of a structure.
Local Stress-Relief Heat Treatment: Stress-relief heat treatment of a specific portion of a structure.
Locked-Up Stress: See Residual Stress.
Longitudinal Seam Welding: The making of a seam weld in a direction essentially parallel to the throat depth of a resistance welding machine.
Longitudinal Sequence: The order in which the increments of a continuous weld are deposited with respect to its length. See Backstep Sequence, Block Sequence, etc.

M

Machine Oxygen Cutting: Oxygen cutting with equipment which performs the cutting operation under the constant observation and control of an operator. The equipment may or may not perform the loading and unloading of the work. See Automatic Oxygen Cutting.
Machine Welding: Welding with equipment which performs the welding operation under the observation and control of an operator. The equipment may or may not perform the loading and unloading of the work. See Automatic Welding.

Manifold: A multiple header for connecting several cylinders to one or more torch supply lines.

Manual Oxygen Cutting: Oxygen cutting wherein the entire cutting operation is performed and controlled by hand. See Automatic Oxygen Cutting and Machine Oxygen Cutting.

Manual Welding: Welding wherein the entire welding operation is performed and controlled by hand. See Automatic Welding and Machine Welding.

Mash Seam Weld: A seam weld made in a lap joint wherein the thickness at the lap is reduced plastically to approximately the thickness of one of the lapped parts.

Melting Rate: The weight or length of electrode melted in a unit of time.

Metal-Arc Cutting: An arc-cutting process wherein the severing of metals is effected by melting with the heat of an arc between a metal electrode and the base metal.

Metal-Arc Welding: See Shielded Metal-Arc Welding, Impregnated-Tape Metal-Arc Welding, Submerged Arc Welding, Atomic Hydrogen Welding, Bare Metal-Arc Welding, Inert-Gas Metal-Arc Welding, Stud Welding and Shielded Stud Welding.

Metal Electrode: A filler- or non-filler-metal electrode, used in arc welding, consisting of a metal wire, with or without a covering or coating.

Metal-Electrode Arc Welding: A group of arc-welding processes wherein metal electrodes are used. See Shielded Metal-Arc Welding, Impregnated-Tape Metal-Arc Welding, Atomic Hydrogen Welding, Inert-Gas Metal-Arc Welding, Submerged Arc Welding, Shielded Stud Welding, Stud Welding and Bare Metal-Arc Welding.

Mixing Chamber: That part of a gas-welding or oxygen-cutting torch wherein the gases are mixed.

Multiple-Impulse Welding: The making of spot, projection and upset welds by more than one impulse of current. When alternating current is used, each impulse may consist of a fraction of a cycle or a number of cycles.

Multiple-Impulse Weld Timer: In resistance welding, a device for multiple-impulse welding which controls only the heat time, the cool time, and either the weld interval or the number of heat times.

N

Neutral Flame: A gas flame wherein the portion used is neither oxidizing nor reducing. See Fig. 37.

Nonpressure Thermit Welding: A thermit-welding process wherein coalescence is produced by heating with superheated liquid metal resulting from the chemical reaction between a metal oxide and aluminum, without the application of pressure. Filler metal is obtained from the liquid metal.

Nonsynchronous Initiation: In resistance welding the initiation or termination of the welding transformer primary current at any random time with respect to the voltage wave.

Nonsynchronous Timing: See Nonsynchronous Initiation.

Nugget: The weld metal joining the parts in spot, seam or projection welds.

O

Off Time: In resistance welding the time during which the electrodes are off the work. This term is generally applied where the welding cycle is repetitive. See Figs. 53 to 57.

Open-Circuit Voltage: In arc welding, the voltage between the terminals of a power source when no current is flowing in the circuit.

Overhead Position: The position of welding wherein welding is performed from the underside of the joint. See Figs. 1 and 2.

Overlap: Protrusion of weld metal beyond the bond at the toe of the weld. See Fig. 40.

Oxidizing Flame: A gas flame wherein the portion used has an oxidizing effect. See Fig. 38.

Oxy-Acetylene Cutting: An oxygen-cutting process wherein the severing of metals is effected by means of the chemical reaction of oxygen with the base metal at elevated temperatures, the necessary temperature being maintained by means of gas flames obtained from the combustion of acetylene with oxygen.

Oxy-Acetylene Welding: A gas-welding process wherein coalescence is produced by heating with a gas flame or flames obtained from the combustion of acetylene with oxygen, with or without the application of pressure and with or without the use of filler metal.

Oxy-Arc Cutting: An oxygen-cutting process wherein the severing of metals is effected by means of the chemical reaction of oxygen with the base metal at elevated temperatures, the necessary temperature being maintained by means of an arc between an electrode and the base metal.

Oxy-City Gas Cutting: An oxygen-cutting process wherein the severing of metals is effected by means of the chemical reaction of oxygen with the base metal at elevated temperatures, the necessary temperature being maintained by means of gas flames obtained from the combustion of city gas with oxygen.

Oxy-Hydrogen Cutting: An oxygen-cutting process wherein the severing of metals is effected by means of the chemical reaction of oxygen with the base metal at elevated temperatures, the necessary temperature being maintained by means of gas flames obtained from the combustion of hydrogen with oxygen.

Oxy-Hydrogen Welding: A gas-welding process wherein coalescence is produced by heating with a gas flame or flames obtained from the combustion of hydrogen with oxygen, without the application of pressure and with or without the use of filler metal.

Oxy-Natural Gas Cutting: An oxygen-cutting process wherein the severing of metals is effected by means of the chemical reaction of oxygen with the base metal at elevated temperatures, the necessary temperature being maintained by means of gas flames obtained from the combustion of natural gas with oxygen.

Oxy-Propane Cutting: An oxygen-cutting process wherein the severing of metals is effected by means of the chemical reaction of oxygen with the base metal at elevated temperatures, the necessary temperature being maintained by means of gas flames obtained from the combustion of propane with oxygen.

Oxygen Cutter: One who is capable of performing a manual oxygen-cutting operation.

Oxygen Cutting: A group of cutting processes wherein the severing of metals is effected by means of the chemical reaction of oxygen with the base metal at elevated temperatures. In the case of oxidation-resistant metals the reaction is facilitated by use of a flux. See Oxy-Acetylene Cutting, Oxy-Arc Cutting, Oxy-City Gas Cutting, Oxy-Hydrogen Cutting, Oxy-Natural Gas Cutting, Oxy-Propane Cutting, Oxy-Lance Cutting and Flux-Oxygen Cutting.

Oxygen-Cutting Operator: One who operates machine or automatic oxygen-cutting equipment.

Oxygen Gouging: An application of oxygen cutting wherein a chamfer or groove is formed.

Oxygen Lance: A length of pipe used to convey oxygen to the point of cutting in oxygen-lance cutting.

Oxygen-Lance Cutting: An oxygen-cutting process wherein only oxygen is supplied by the lance and the preheat is obtained by other means.

Oxygen Lancing: See Oxygen-Lance Cutting.

P

Parent Metal: See Base Metal.

Partial Joint Penetration: Joint penetration which is less than complete. See Fig. 30.

Pass: A single longitudinal progression of a welding operation along a joint or weld deposit. The result of a pass is a weld bead.

Peening: The mechanical working of metals by means of hammer blows.

Penetration: See Joint Penetration and Root Penetration.

Percussion Weld: A weld made by percussion welding.

Percussion Welding: A resistance-welding process wherein coalescence is produced, simultaneously over the entire area of abutting surfaces, by the heat obtained from an arc produced by a rapid discharge of stored electrical energy, with pressure precussively applied during or immediately following the electrical discharge.

Platen: In a resistance-welding machine, a member with a substantially flat surface to which dies, fixtures, backups or electrode holders are attached, and which transmits the electrode force or upsetting force.

Platen Force: In flash and upset welding the force available at the movable platen to cause upsetting. This force may be dynamic, theoretical or static.

Platen Spacing: See Horn Spacing.

Plug Weld: A circular weld made by either arc or gas welding through one member of a lap or tee joint joining that member to the other. The weld may or may not be made through a hole in the first member. If a hole is used the walls may or may not be parallel and the hole may be partially or completely filled with weld metal. (A fillet-welded hole or a spot weld should not be construed as conforming to this definition.) See Fig. 14.

Poke Weld: See Push Weld.

Poke Welding: See Push Welding.

Porosity: Gas pockets or voids in metal.

Positioned Weld: A weld made in a joint which has been so placed as to facilitate making the weld.

Position of Welding: See Flat, Horizontal, Vertical and Overhead Positions and Horizontal Rolled, Horizontal Fixed and Vertical Pipe Positions.

Postheating: The application of heat to a weld or weldment subsequent to a welding or cutting operation.

Postweld Interval: In resistance welding, the heat time between the end of weld time, or weld interval, and the start of hold time. During this interval the weld is subjected to mechanical and heat treatment. See Fig. 54.

Preheating: The application of heat to the base metal prior to a welding or cutting operation.

Pressure-Controlled Welding: The making of a number of spot or projection welds wherein several electrodes progressively function under the control of a pressure-sequencing device.

Pressure Gas Welding: A gas-welding process wherein coalescence is produced, simultaneously over the entire area of abutting surfaces, by heating with gas flames obtained from the combustion of a fuel gas with oxygen and by the application of pressure, without the use of filler metal.

Pressure Thermit Welding: A thermit-welding process wherein coalescence is produced by heating with superheated liquid metal and slag resulting from the chemical reaction between iron oxide and aluminum, and by applying pressure. The liquid metal from the reaction is not used as filler metal.

Pressure Welding: Any welding process or method wherein pressure is used to complete the weld.

Preweld Interval: In spot, projection and upset welding, the time between the end of squeeze time and the start of weld time, or weld interval, during which the material is preheated. In flash welding, the time during which the material is preheated. See Fig. 53, 54, 56 and 57.

Progressive Block Sequence: A block sequence wherein successive blocks are completed progressively along the joint, either from one end to the other or from the center of the joint toward either end.

Projection Weld: A weld made by projection welding.

Projection Welding: A resistance-welding process wherein coalescence is produced by the heat obtained from resistance to the flow of electric current through the work parts held together under pressure by electrodes. The resulting welds are localized at predetermined points by the design of the parts to be welded. The localization is usually accomplished by projections, embossments or intersections.

Pulsation Welding: See Multiple-Impulse Welding.

Pulsation Weld Timer: See Multiple-Impulse Weld Timer.

Push Weld: A spot or projection weld made by push welding.

Push Welding: The making of a spot or projection weld wherein the force is applied manually to one electrode and the work or a backing bar takes the place of the other electrode.

Q

Quench Time: In resistance welding, that part of the postweld interval from the cessation of flow of welding current to the application of a current impulse for postheating. See Figs. 54 and 56.

R

Random Sequence: See Wandering Sequence.
Rate of Deposition: See Deposition Rate.
Rate of Flame Propagation: The speed at which a flame travels through a mixture of gases.
Reaction Stress: The residual stress which could not otherwise exist if the members or parts being welded were isolated as free bodies without connection to other parts of the structure.
Reactor: A device used in arc-welding circuits for the purpose of minimizing irregularities in the flow of welding current.
Reducing Flame: A gas flame wherein the portion used has a reducing effect. See Fig. 39.
Regulator: A device for controlling the delivery of gas at some substantially constant pressure regardless of variation in the higher pressure at the source.
Reinforcement of Weld: Weld metal on the face of a groove weld in excess of the metal necessary for the specified weld size. See Fig. 42.
Residual Stress: Stress remaining in a structure or member as a result of thermal or mechanical treatment or both.
Resistance Brazing: A brazing process wherein coalescence is produced by the heat obtained from resistance to the flow of electric current in a circuit of which the work is a part and by using a nonferrous filler metal, having a melting point above 800° F. but below that of the base metals. The filler metal is distributed in the joint by capillary attraction.
Resistance Butt Weld: See Upset Weld and Flash Weld.
Resistance Butt Welding: See Upset Welding and Flash Welding.
Resistance Welding: A group of welding processes wherein coalescence is produced by the heat obtained from resistance of the work to the flow of electric current in a circuit of which the work is a part, and by the application of pressure.
Resistance Welding Electrode: See Electrode.
Reverse Polarity: The arrangement of direct current arc-welding leads wherein the work is the negative pole and the electrode is the positive pole of the welding arc. See Fig. 34.
Roll Spot Welding: The making of separated spot welds with circular electrodes.
Roll Welding: A forge-welding process wherein coalescence is produced by heating in a furnace and by applying pressure by means of rolls.
Root: See Root of Joint and Root of Weld.
Root Crack: A crack in the weld or base metal occurring at the root of a weld.
Root Edge: A root face of zero width. See Root Face. See Fig. 19.
Root Face: That portion of the groove face adjacent to the root of the joint. See Fig. 19.
Root Gap: See Root Opening.
Root of Joint: That portion of a joint to be welded where the members approach closest to each other. In cross-section the root of the joint may be either a point, a line or an area. See Fig. 43.
Root of Weld: The points, as shown in cross-section, at which the bottom of the weld intersects the base metal surfaces. See Fig. 44.

Root Opening: The separation between the members to be joined, at the root of the joint. See Fig. 18.
Root Penetration: The depth a groove weld extends into the root of a joint measured on the centerline of the root cross-section. See Fig. 28.
Root Radius: See Groove Radius.

S

Scarf: See Edge Preparation.
Scarfing: Sec Chamfering.
Seal Weld: Any weld used primarily to obtain tightness.
Seam Weld: A weld consisting of a series of overlapping spot welds, made by seam welding or spot welding. See Fig. 16.
Seam Weld Timer: In seam welding, a device which controls the heat times and the cool times.
Seam Welding: A resistance-welding process wherein coalescence is produced by the heat obtained from resistance to the flow of electric current through the work parts held together under pressure by circular electrodes. The resulting weld is a series of overlapping spot welds made progressively along a joint by rotating the electrodes.
Selective Block Sequence: A block sequence wherein successive blocks are completed in a certain order selected to create a predetermined stress pattern.
Semi-Automatic Arc Welding: Arc welding with equipment which controls only the filler metal feed. The advance of the welding is manually controlled.
Series Welding: The making of two spot or seam welds or two or more projection welds simultaneously with three electrodes forming a series circuit. See Fig. 47.
Sequence Timer: In resistance welding, a device for controlling the sequence and duration of any or all of the elements of a complete welding cycle, except weld time or heat time.
Sequence Weld Timer: In resistance welding, a device for controlling the sequence and duration of any or all of the elements of a complete welding cycle.
Sheet Separation: In spot, seam and projection welding, the gap surrounding the weld, between faying surfaces, after the joint has been welded.
Shielded Carbon-Arc Welding: An arc-welding process wherein coalescence is produced by heating with an electric arc between a carbon electrode and the work. Shielding is obtained from the combustion of a solid material fed into the arc or from a blanket of flux on the work or both. Pressure may or may not be used and filler metal may or may not be used.
Shielded Metal-Arc Welding: An arc-welding process wherein coalescence is produced by heating with an electric arc between a covered metal electrode and the work. Shielding is obtained from decomposition of the electrode covering. Pressure is not used and filler metal is obtained from the electrode.
Shielded Stud Welding: An arc-welding process wherein coalescence is produced by heating with an electric arc drawn between a metal-stud,

or similar part, and the other work part, until the surfaces to be joined are properly heated, when they are brought together under pressure. Shielding is obtained from an inert gas such as helium or argon.

Shoulder: See Root Face.

Shrinkage Stress: See Residual Stress.

Single-Bevel Groove Weld: A type of groove weld. See Fig. 12.

Single-Impulse Welding: The making of spot projection and upset welds by a single impulse of current. When alternating current is used, an impulse may consist of a fraction of a cycle or a number of cycles.

Single-J Groove Weld: A type of groove weld. See Fig. 12.

Single-U Groove Weld: A type of groove weld. See Fig. 12.

Single-Vee Groove Weld: A type of groove weld. See Fig. 12.

Size of Weld:

Groove Weld.—The joint penetration (depth of chamfering plus the root penetration when specified). See Fig. 45.

Fillet Weld.—For equal leg fillet welds, the leg length of the largest isosceles right-triangle which can be inscribed within the fillet-weld cross-section. See Fig. 46.

For unequal leg fillet welds, the leg lengths of the largest right-triangle which can be inscribed within the fillet-weld cross-section. See Fig. 46.

Skip Sequence: See Wandering Sequence.

Slag Inclusion: Non-metallic solid material entrapped in weld metal or between weld metal and base metal.

Slot Weld: A weld made in an elongated hole in one member of a lap or tee joint joining that member to that portion of the surface of the other member which is exposed through the hole. The hole may be open at one end and may be partially or completely filled with weld metal. (A fillet-welded slot should not be construed as conforming to this definition.) See Fig. 15.

Slugging: The act of adding a separate piece or pieces of material in a joint before or during welding resulting in a welded joint which does not comply with design, drawing or specification requirements.

Spacer Strip: A metal strip or bar inserted in the root of a joint prepared for a groove weld to serve as a backing and to maintain root opening during welding. See Fig. 48.

Spatter: In arc and gas welding, the metal particles expelled during welding and which do not form a part of the weld.

Spatter Loss: Metal lost due to spatter.

Spit: See Flash.

Spot Weld: A weld made by spot welding. See Fig. 16.

Spot Welding: A resistance-welding process wherein coalescence is produced by the heat obtained from resistance to the flow of electric current through the work parts held together under pressure by electrodes. The size and shape of the individually formed welds are limited primarily by the size and contour of the electrodes.

Square Groove Weld: A type of groove weld. See Fig. 12.

Squeeze Time: In spot, seam projection and upset welding, the time interval between the initial application of the electrode force on the work and the first application of current. See Figs. 53, 54, 55 and 57.

Stack Cutting: Oxygen cutting of stacked metal plates arranged so that all the plates are severed by a single cut.

Staggered Intermittent Fillet Welding: Two lines of intermittent fillet welding on a joint wherein the fillet weld increments in one line are staggered with respect to those in the other line. See Fig. 24.

Static Electrode Force: See Electrode Force.

Stepback Sequence: See Backstep Sequence.

Stored Energy Welding: The making of a weld with electrical energy accumulated electrostatically, electromagnetically or electrochemically at a relatively low rate and made available at the required welding rate.

Straight Polarity: The arrangement of direct current arc-welding leads wherein the work is the positive pole and the electrode is the negative pole of the welding arc. See Fig. 35.

Stress-Relief Heat Treatment: Uniform heating of a structure or portion thereof to a sufficient temperature, below the critical range, to relieve the major portion of the residual stresses, followed by uniform cooling. (*Note:* Terms normalizing, annealing, etc., are misnomers for this application.)

String Bead: A type of weld bead made without appreciable transverse oscillation. See Fig. 49.

String Beading: The deposition of string beads.

Stud Welding: An arc-welding process wherein coalescence is produced by heating with an electric arc drawn between a metal stud, or similar part, and the other work part until the surfaces to be joined are properly heated, when they are brought together under pressure, and no shielding is used.

Submerged Arc Welding: An arc-welding process wherein coalescence is produced by heating with an electric arc or arcs between a bare metal electrode or electrodes and the work. The welding is shielded by a blanket of granular, fusible material on the work. Pressure is not used and filler metal is obtained from the electrode and sometimes from a supplementary welding rod.

Surfacing: The deposition of filler metal on a metal surface to obtain desired properties or dimensions.

Synchronous Initiation: In spot, seam and projection welding, the initiation and termination of each half-cycle of welding-transformer primary current so that all half-cycles of such current are identical.

Synchronous Timing: See Synchronous Initiation.

T

Tack Weld: A weld made to hold parts of a weldment in proper alignment until the final welds are made.

Tee Joint: A joint between two members located approximately at right angles to each other in the form of a *T*. See Fig. 17.

Temper Time: In resistance welding, that part of the postweld interval during which a current suitable for tempering or heat treatment flows. The current can be single or multiple impulse, with varying heat and cool intervals. See Figs. 54 and 56.

Theoretical Electrode Force: See Electrode Force.

Thermit Crucible: The vessel in which the thermit reaction takes place.

Thermit Mixture: A mixture of metal oxide and finely divided aluminum with the addition of alloying metals as required.

Thermit Mold: A mold formed around the parts to be welded to receive the molten metal.

Thermit Reaction: The chemical reaction between metal oxide and aluminum which produces superheated molten metal and aluminum oxide slag.

Thermit Welding: A group of welding processes wherein coalescence is produced by heating with superheated liquid metal and slag resulting from a chemical reaction between a metal oxide and aluminum, with or without the application of pressure. Filler metal, when used, is obtained from the liquid metal.

Throat Depth: In a resistance-welding machine, the distance from the center-line of the electrodes or platens to the nearest point of interference for flatwork or sheets. In the case of a seam-welding machine with a universal head, the throat depth is measured with the machine arranged for transverse welding.

Throat of a Fillet Weld:

Theoretical.—The distance from the beginning of the root of the joint perpendicular to the hypotenuse of the largest right-triangle that can be inscribed within the fillet-weld cross-section. See Figs. 31 and 32.

Actual.—The shortest distance from the root of a fillet weld to its face. See Figs. 31 and 32.

Throat Opening: See Horn Spacing.

Tip Skid: See Electrode Skid.

Toe Crack: A crack in the base metal occurring at the toe of a weld. See Fig. 51.

Toe of Weld: The junction between the face of a weld and the base metal. See Fig. 20.

Torch: See Welding Torch or Cutting Torch.

Torch Brazing: A brazing process wherein coalescence is produced by heating with a gas flame and by using a nonferrous filler metal having a melting point above 800° F. but below that of the base metal. The filler metal is distributed in the joint by capillary attraction.

Torch Tip: See Welding Tip or Cutting Tip.

Transverse Seam Welding: The making of a seam weld in a direction essentially at right angles to the throat depth of a seam welding machine.

Tungsten Electrode: A non-filler-metal electrode, used in arc welding, consisting of a tungsten wire.

Twin-Carbon Arc Brazing: A brazing process wherein coalescence is produced by heating with an electric arc maintained between two carbon electrodes and by using a nonferrous filler metal, having a melting point above 800° F. but below that of the base metals. The filler metal is distributed in the joint by capillary attraction.

Twin-Carbon Arc Welding: An arc-welding process wherein coalescence is produced by heating with an electric arc maintained between two carbon electrodes and no shielding is used. Pressure is not used and filler metal may or may not be used.

U

Ultra-Speed Welding: See Commutator-Controlled Welding.
Underbead Crack: A crack in the heat-affected zone not extending to the surface of the base metal. See Fig. 52.
Undercut: A groove melted into the base metal adjacent to the toe of a weld and left unfilled by weld metal. See Fig. 40.
Upset: The localized increase in volume in the region of a weld, resulting from the application of pressure.
Upset Butt Welding: See Upset Welding.
Upset Weld: A weld made by upset welding. See Fig. 16.
Upset Welding: A resistance-welding process wherein coalescence is produced, simultaneously over the entire area of abutting surfaces or progressively along a joint, by the heat obtained from resistance to the flow of electric current through the area of contact of those surfaces. Pressure is applied before heating is started and is maintained throughout the heating period.
Upsetting Force: In flash and upset welding, the force exerted at the welding surfaces during upsetting.
Upsetting Time: In flash and upset welding, the time during upsetting. See Figs. 56 and 57.

V

Vertical Position: The position of welding wherein the axis of the weld is approximately vertical. See Figs. 1 and 2.
Vertical Position:
Pipe Welding.—The position of a pipe joint wherein welding is performed in the horizontal position and the pipe may or may not be rotated. See Fig. 3.
Voltage Regulator: An automatic electrical control device for maintaining a constant voltage supply to the primary of a welding transformer.

W

Wandering Block Sequence: A block sequence wherein successive blocks are completed at random after several starting blocks have been completed.
Wandering Sequence: A longitudinal sequence wherein the weld bead increments are deposited at random.
Wax Pattern: Wax molded around the parts to be welded by a thermit welding process, to the form desired for the completed weld.
Weave Bead: A type of weld bead made with transverse oscillation. See Fig. 50.
Weave Beading: The deposition of weave beads.
Weaving: See Weave Beading.
Weld: A localized coalescence of metal wherein coalescence is produced by heating to suitable temperatures, with or without the application of pressure, and with or without the use of filler metal. The filler metal either has a melting point approximately the same as the base metals or has a melting point below that of the base metals but above 800° F.

Weldability: The capacity of a metal to be welded under the fabrication conditions imposed into a specific, suitably designed structure and to perform satisfactorily in the intended service.

Weld Bead: A weld deposit resulting from a pass. See String Bead and Weave Bead. See Fig. 36.

Weld Crack: A crack in weld metal.

Weld Delay Time: In spot and projection welding, the time that the weld time is delayed to insure proper sequence of mechanical functions in relation to subsequent electrical functions. See Fig. 54.

Weld Gage: A device designed for checking the shape and size of welds.

Weld Interval: In resistance welding, the total of all heat and cool times when making a single, multiple-impulse weld. See Figs. 53 to 57.

Weld Interval Timer: In resistance welding, a device which controls heat and cool times and weld interval when making multiple-impulse welds singly or simultaneously.

Weld Line: See Bond.

Weld Metal: That portion of a weld which has been melted during welding.

Weld Metal Area: The area of the weld metal as measured on the cross-section of a weld. See Fig. 41.

Weld Penetration: See Joint Penetration and Root Penetration.

Weld Time: In single-impulse welding and flash welding, the time that welding current is applied to the work in making a weld. See Figs. 53 to 57.

Weld Timer: In resistance welding, a device which controls only the weld time.

Welded Joint: A union of two or more members produced by the application of a welding process.

Welder: One who is capable of performing a manual or semi-automatic welding operation.

Welding (Noun): The metal joining process used in making welds. (See Forge Welding, Thermit Welding, Flow Welding, Gas Welding, Arc Welding, Resistance Welding, Induction Welding and Brazing.)

Welding Current: The current flowing through the welding circuit during the making of a weld. In resistance welding the current used during preweld or postweld intervals is excluded.

Welding Cycle: In resistance welding, the complete series of events involved in the making of a weld. See Figs. 53 to 57.

Welding Electrode: See Electrode.

Welding Force: See Electrode Force and Platen Force.

Welding Generator: A generator used for supplying current for welding.

Welding Goggles: Goggles with tinted lenses, used during welding or oxygen cutting, which protect the eyes from harmful radiation and flying particles.

Welding Ground: See Work Lead.

Welding Leads: The work lead and electrode lead of an arc-welding circuit. See Figs. 34 and 35.

Welding Machine: Equipment used to perform the welding operation. For example, spot-welding machine, arc-welding machine, seam-welding machine, etc.

Welding Operator: One who operates machine or automatic welding equipment.

Welding Pressure: The pressure exerted during the welding operation on the parts being welded. (See also Electrode Force and Platen Force.)

Welding Procedure: The detailed methods and practices including joint welding procedures involved in the production of a weldment.

Welding Process: A metal-joining process wherein coalescence is produced by heating to suitable temperatures, with or without the application of pressure, and with or without the use of filler metal. (See Forge Welding, Thermit Welding, Flow Welding, Gas Welding, Arc Welding, Resistance Welding, Induction Welding, and Brazing.)

Welding Rod: Filler metal, in wire or rod form, used in gas welding and brazing processes, and those arc-welding processes wherein the electrode does not furnish the filler metal.

Welding Sequence: The order of making the welds in a weldment.

Welding Technique: The details of a manual, machine or semi-automatic welding operation which, within the limitations of the prescribed joint welding procedure, are controlled by the welder or welding operator.

Welding Tip: A welding torch tip designed for welding.

Welding Torch: A device used in gas welding or torch brazing for mixing and controlling the flow of gases.

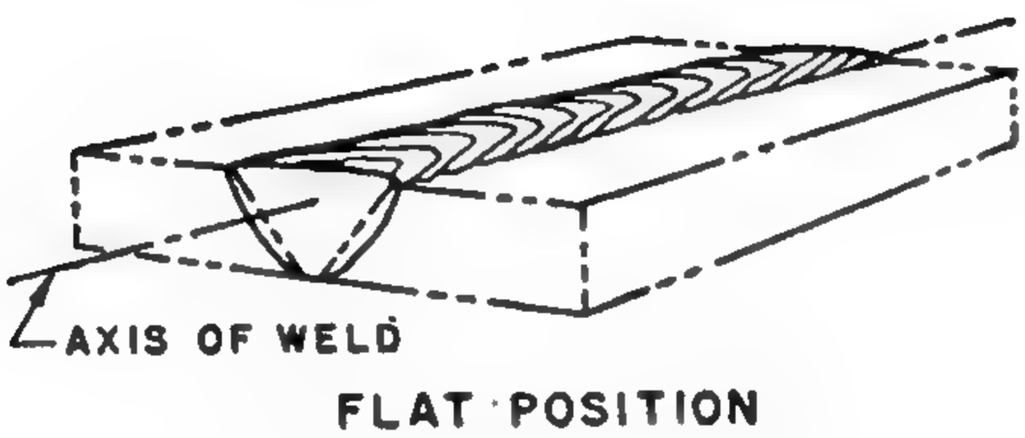
Welding Transformer: A transformer used for supplying current for welding.

Welding Wheel: See Electrode.

Weldment: An assembly whose component parts are joined by welding.

Weldor: See Welder.

Work Lead: The electric conductor between the source of arc-welding current and the work. See Figs. 34 and 35.



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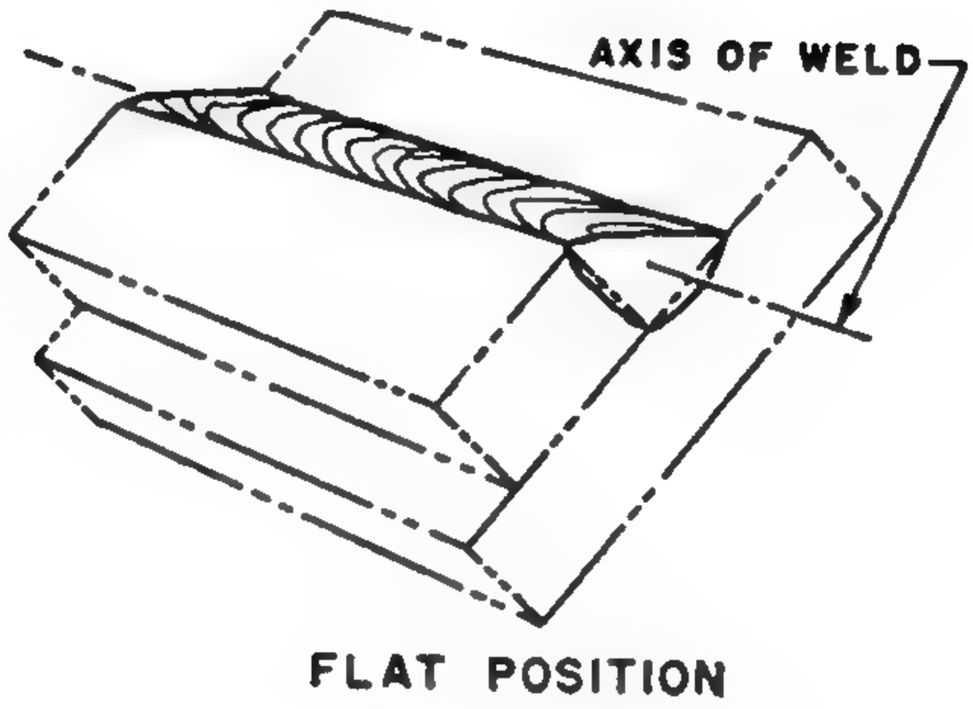

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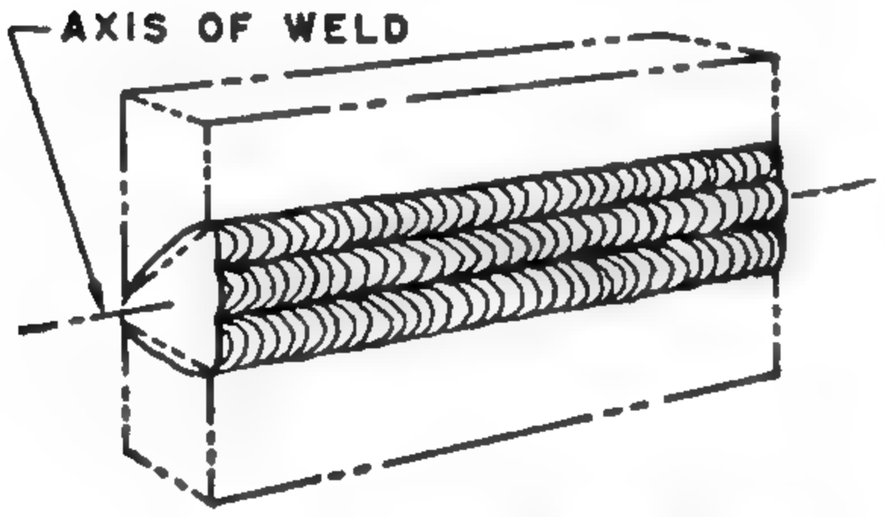

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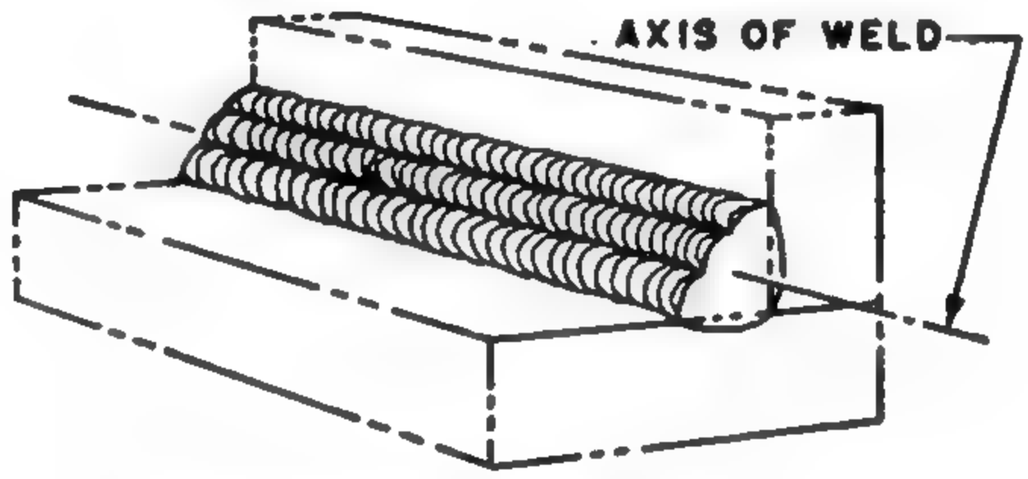

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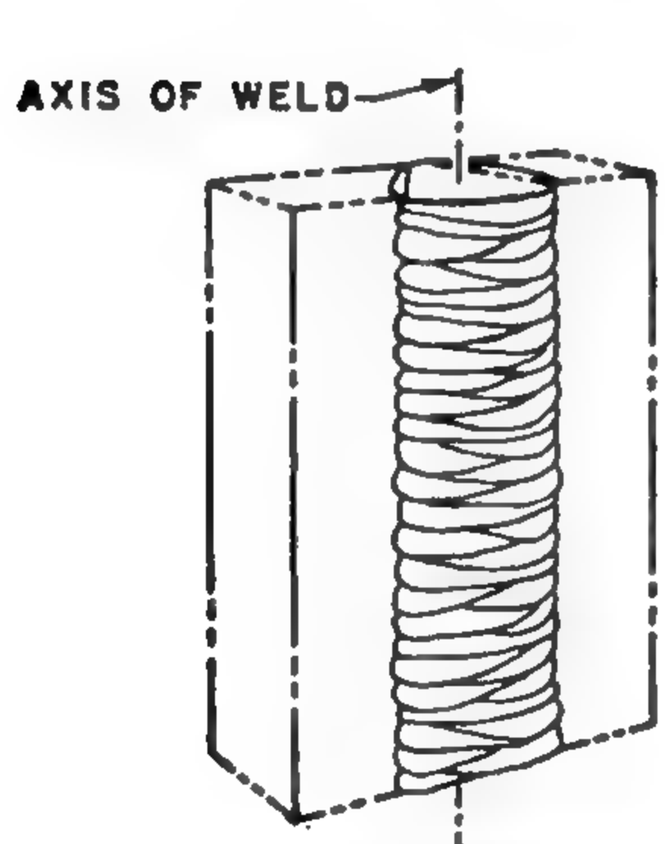

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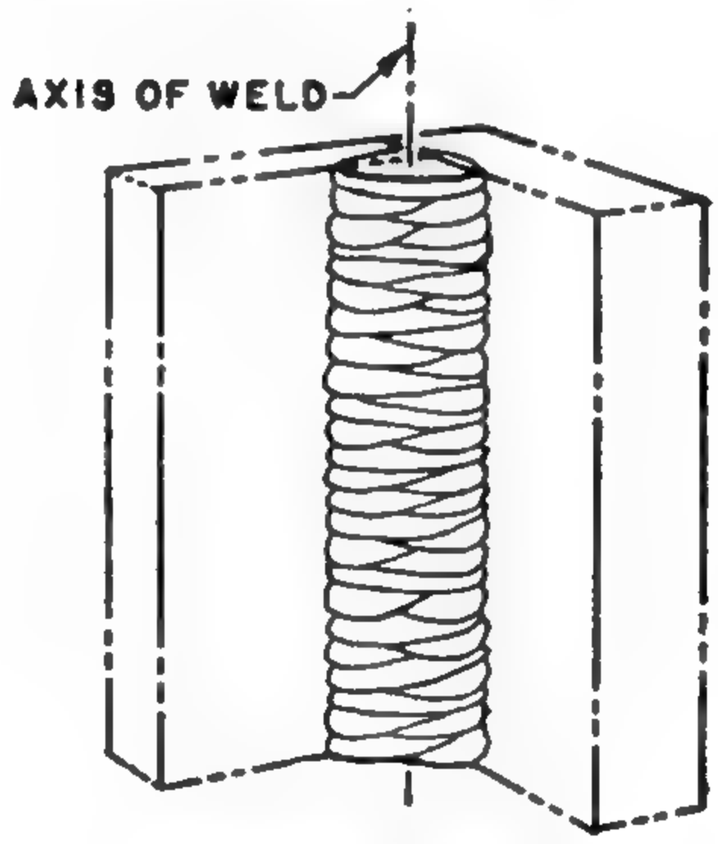

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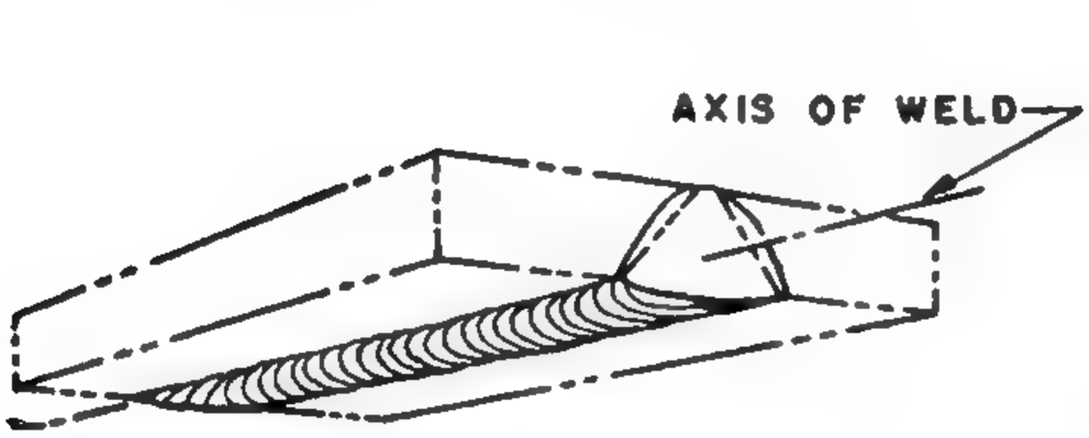
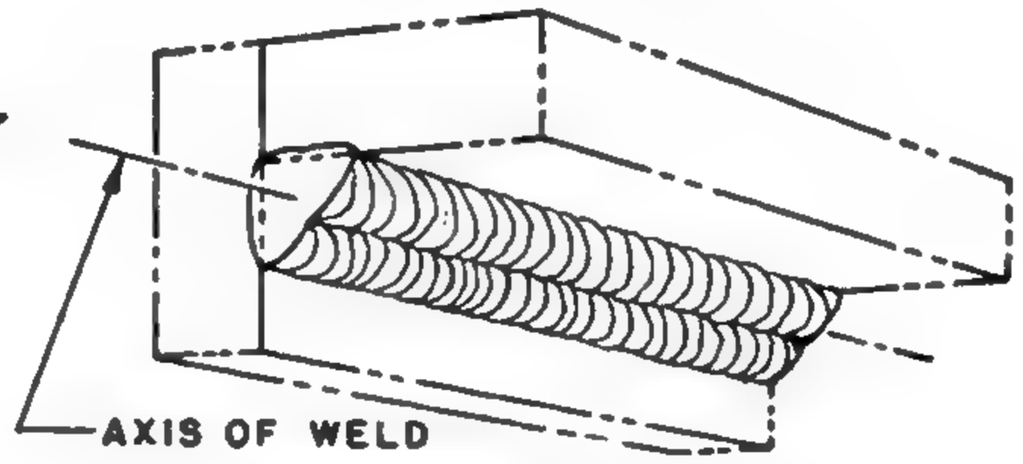


OVERHEAD POSITION



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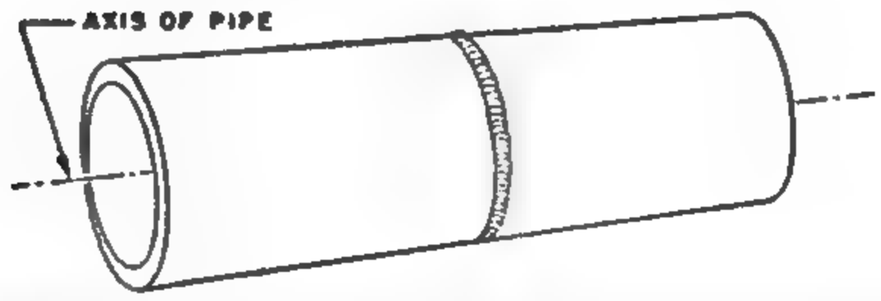
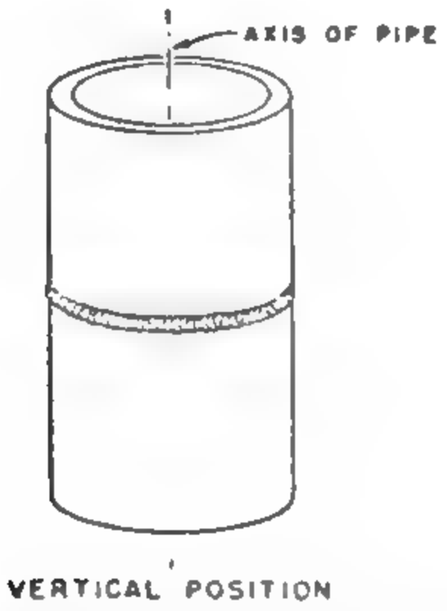


HORIZONTAL FIXED POSITION (PIPE STATIONARY DURING WELDING)
HORIZONTAL ROLLED POSITION (PIPE ROTATED DURING WELDING)



VERTICAL POSITION

Fig. 3.—Positions of Pipe During Welding

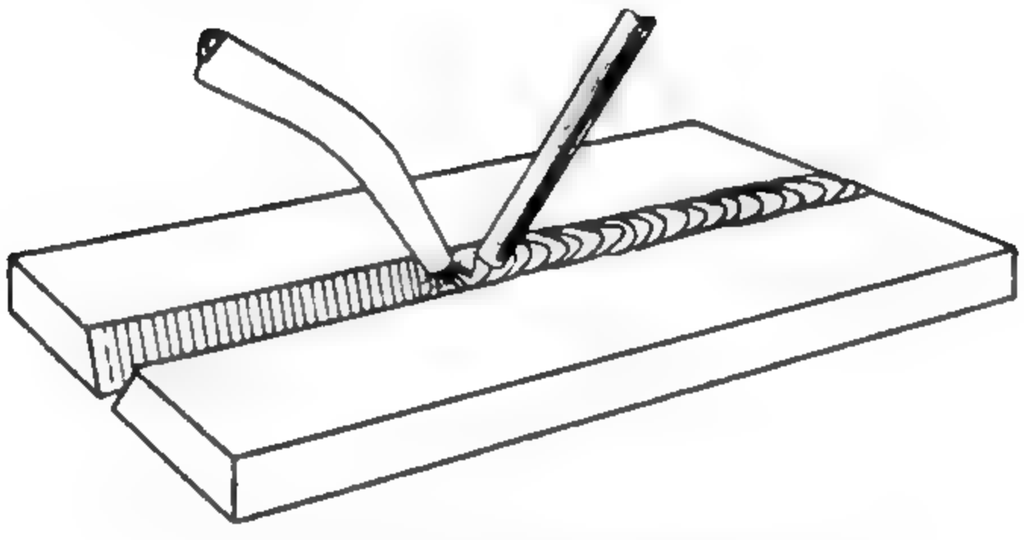


Fig. 4.—Backhand Welding

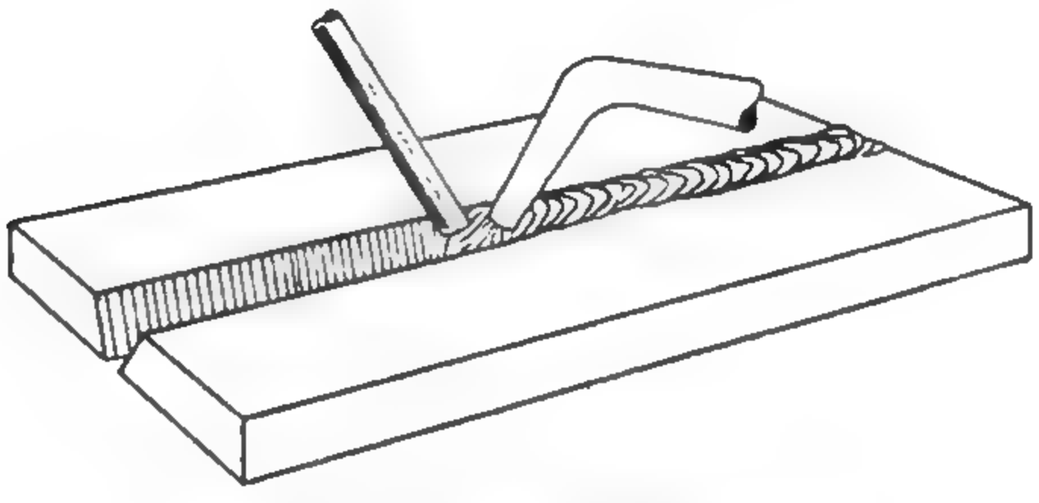


Fig. 5.—Forehand Welding

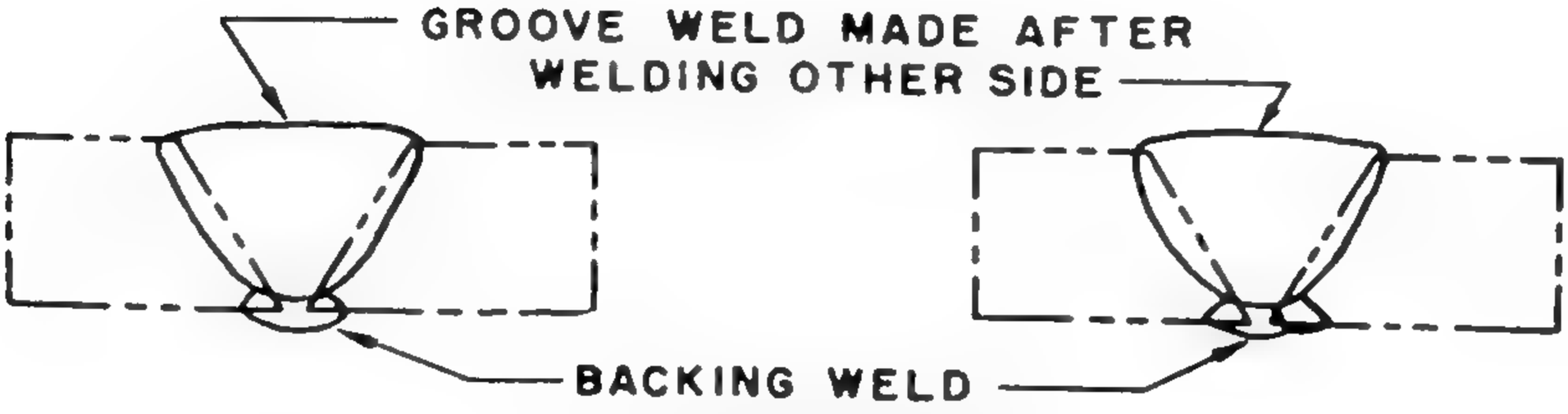


Fig. 6.—Backing Welds

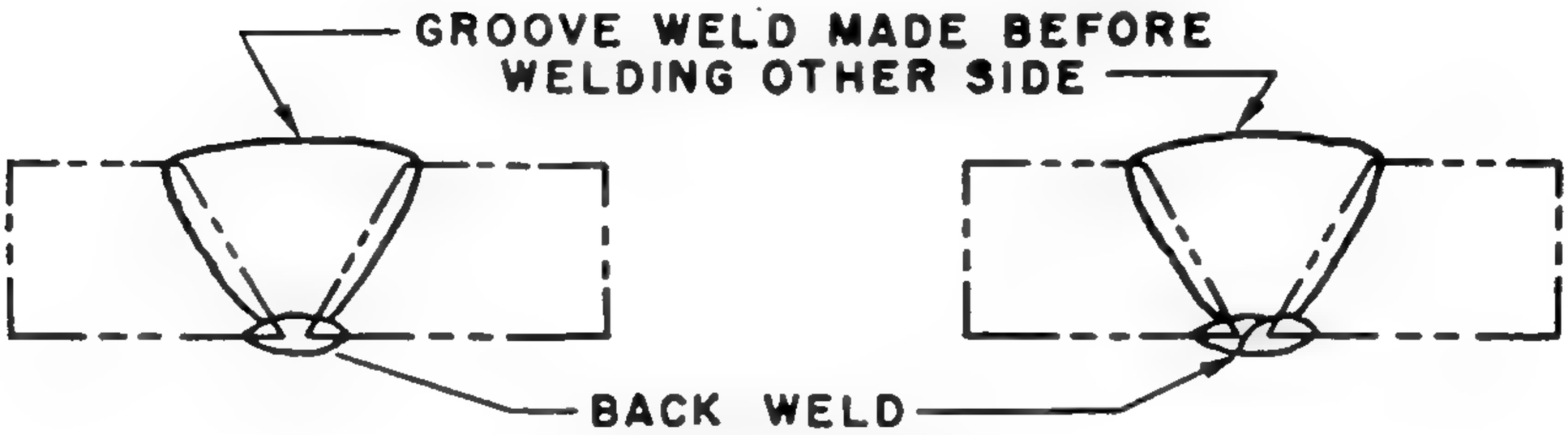


Fig. 7.—Back Welds

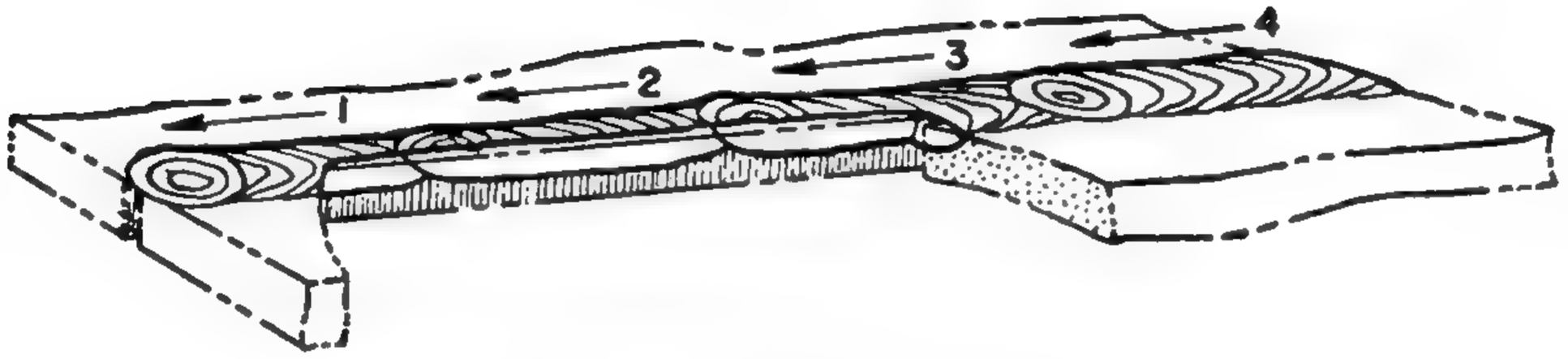


Fig. 8.—Backstep Sequence

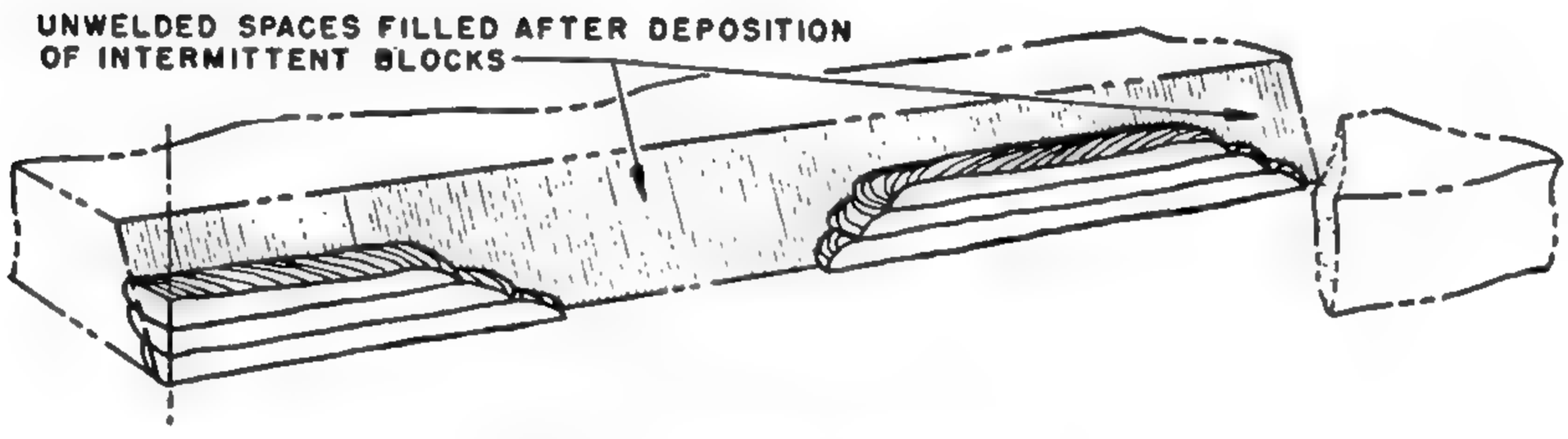


Fig. 9.—Block Sequence

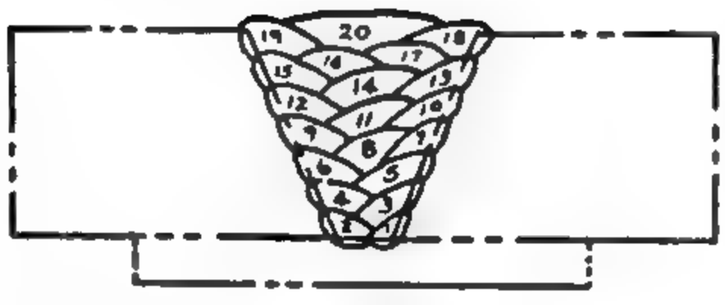
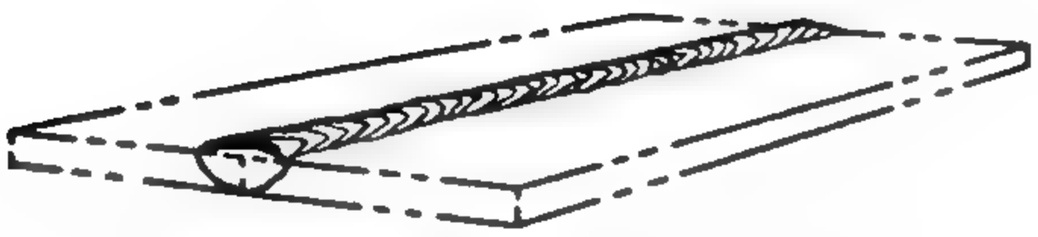
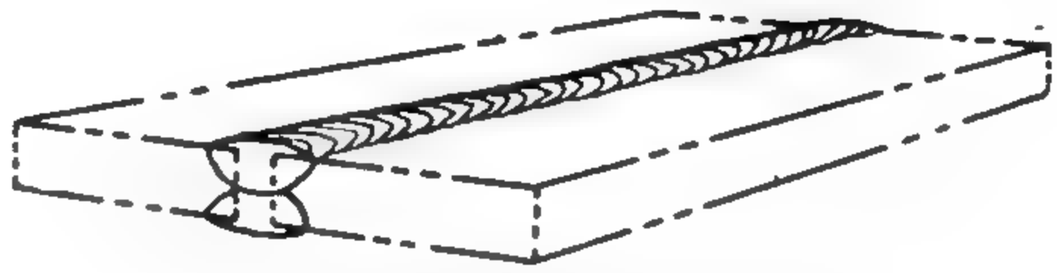


Fig. 10.—Build-Up Sequence

Fig. 11.—Cascade Sequence



SQUARE GROOVE WELD



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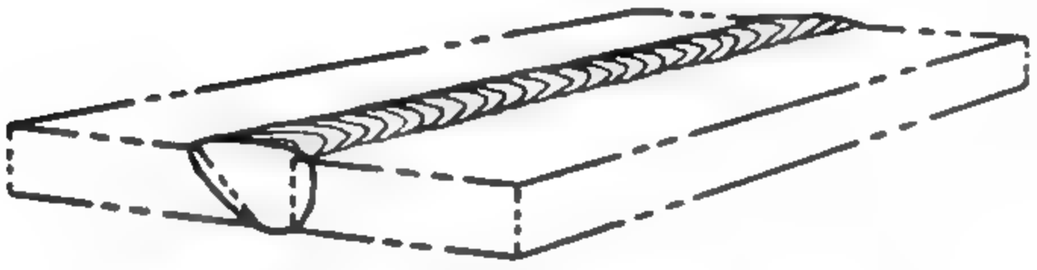
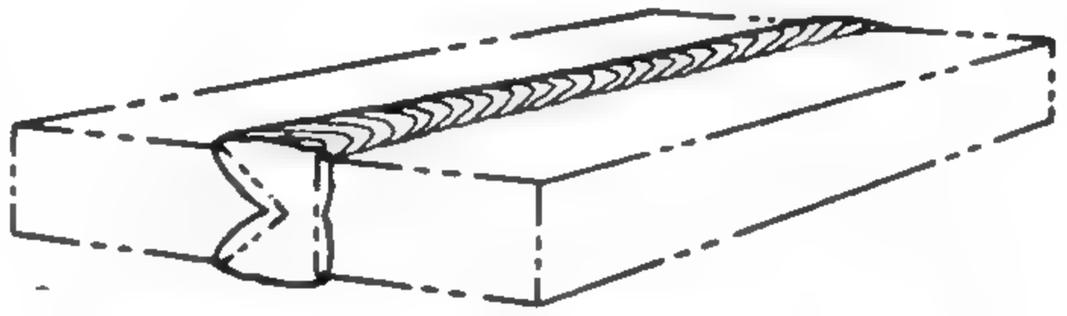
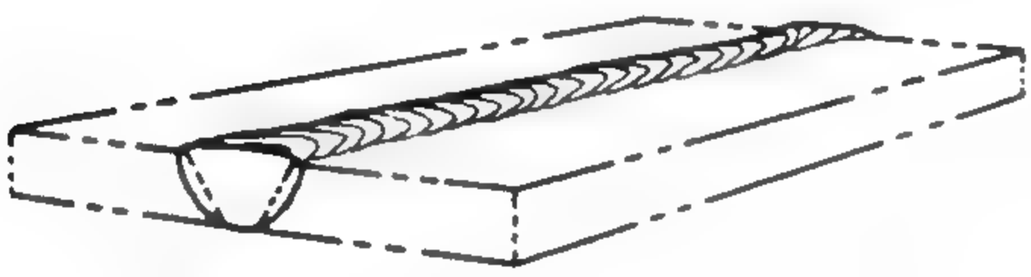


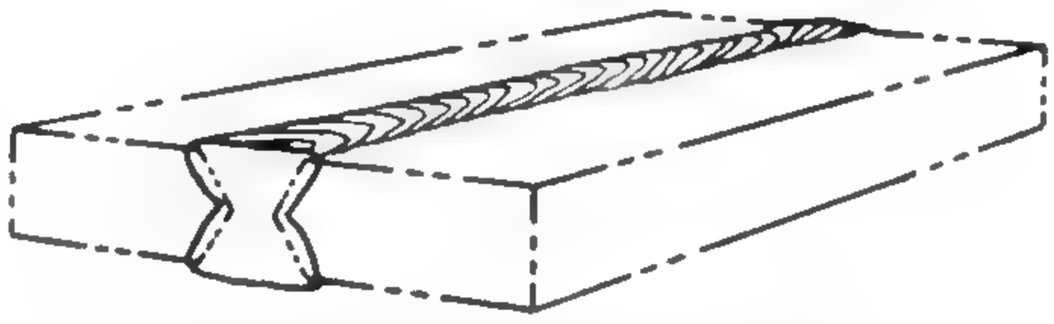
SINGLE-BEVEL GROOVE WELD



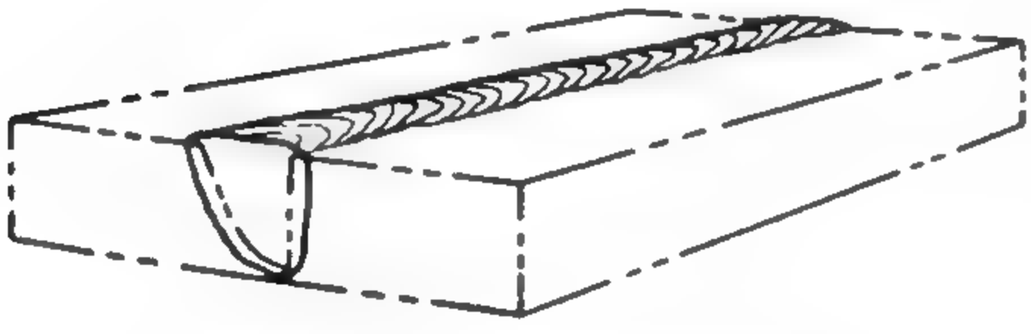
DOUBLE-BEVEL GROOVE WELD



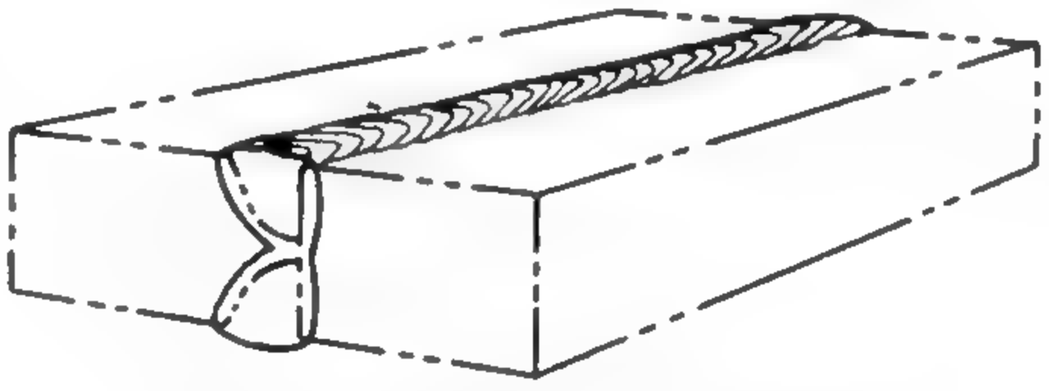
SINGLE-VEE GROOVE WELD



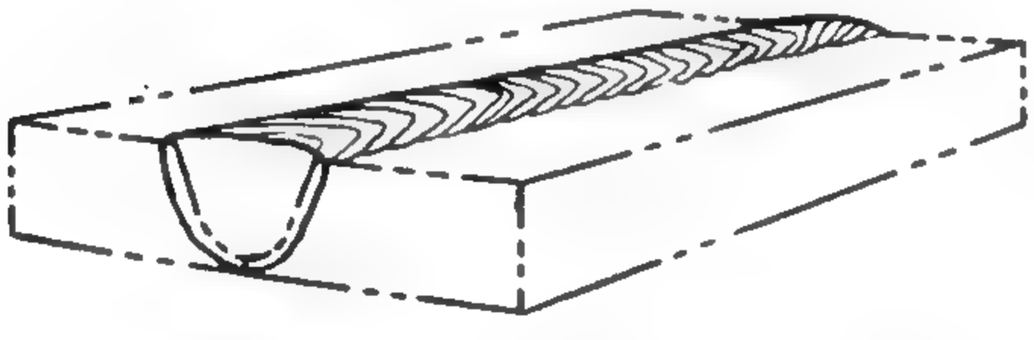
DOUBLE-VEE GROOVE WELD



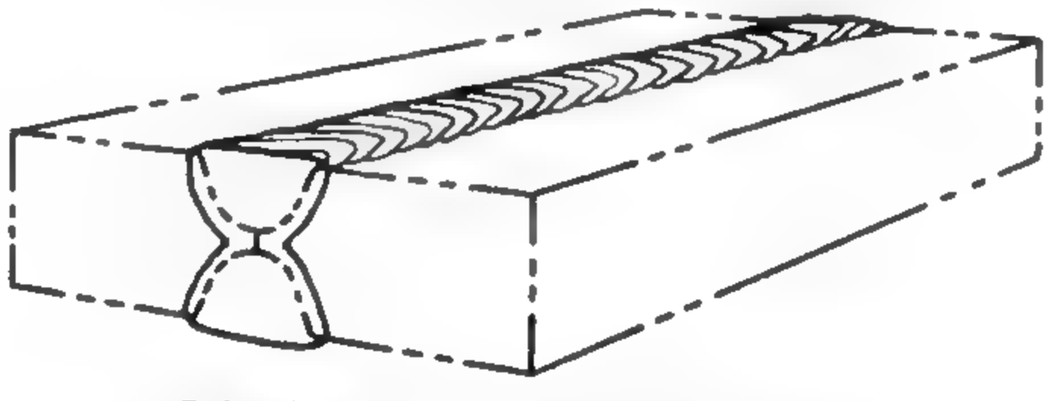
SINGLE-J GROOVE WELD



DOUBLE-J GROOVE WELD

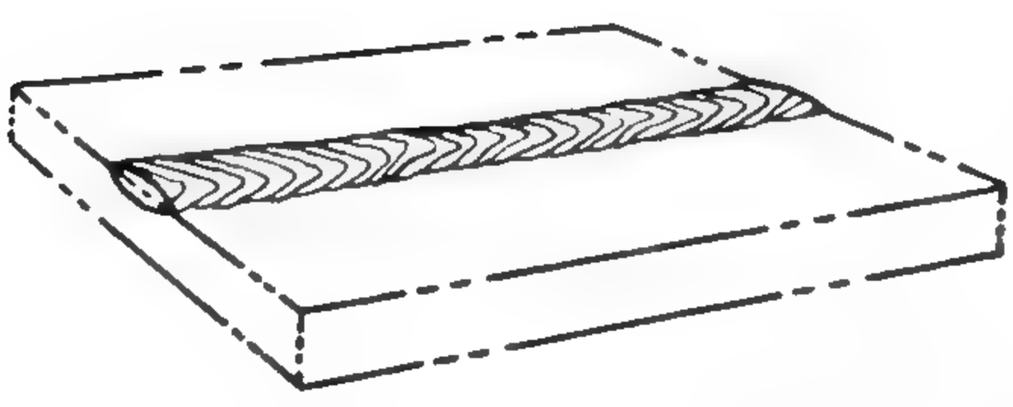


SINGLE-U GROOVE WELD



DOUBLE-U GROOVE WELD

Fig. 12.—Types of Groove Weld



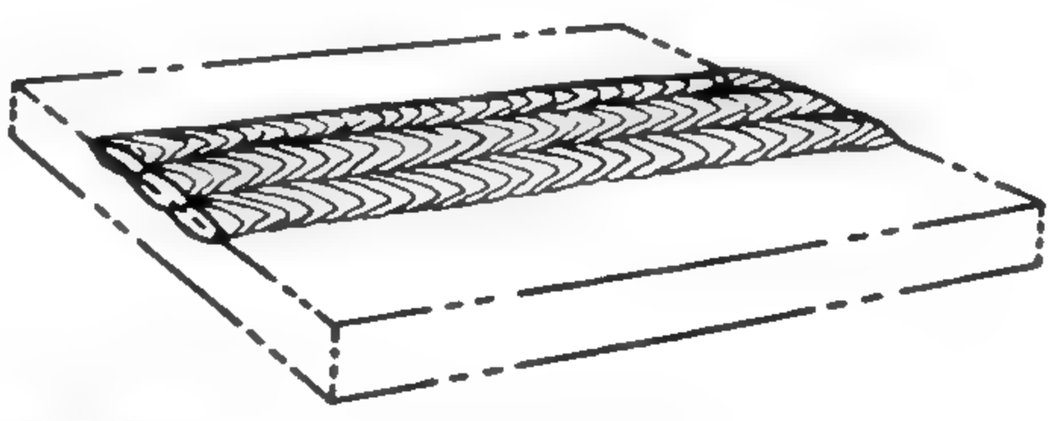
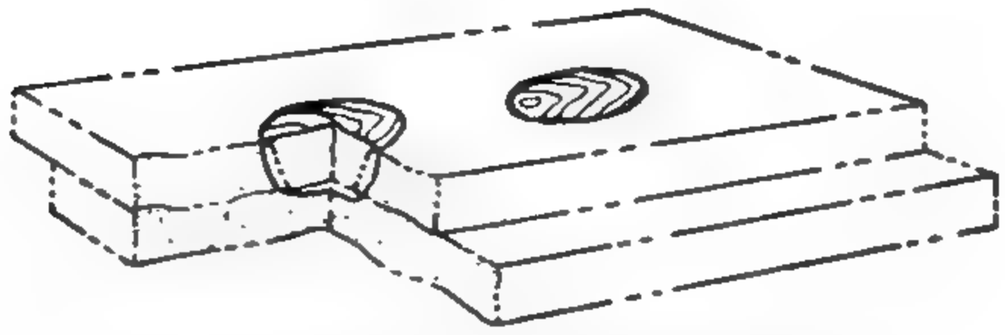
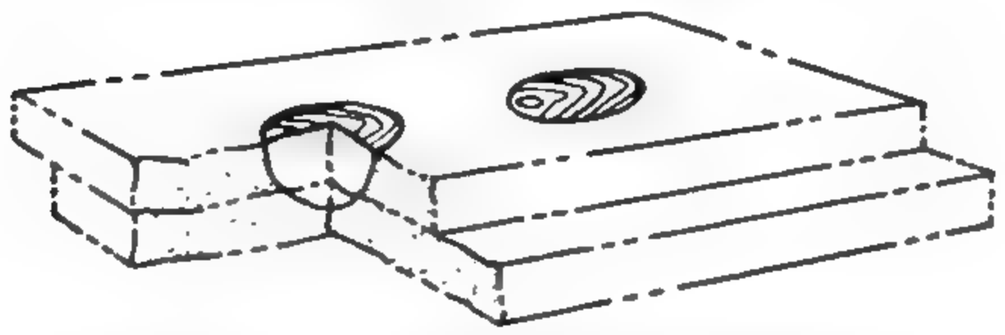


Fig. 13.—Bead Welds



PLUG WELDS MADE THROUGH HOLES



PLUG WELDS MADE THROUGH MEMBER WITHOUT HOLES

Fig. 14.—Plug Welds

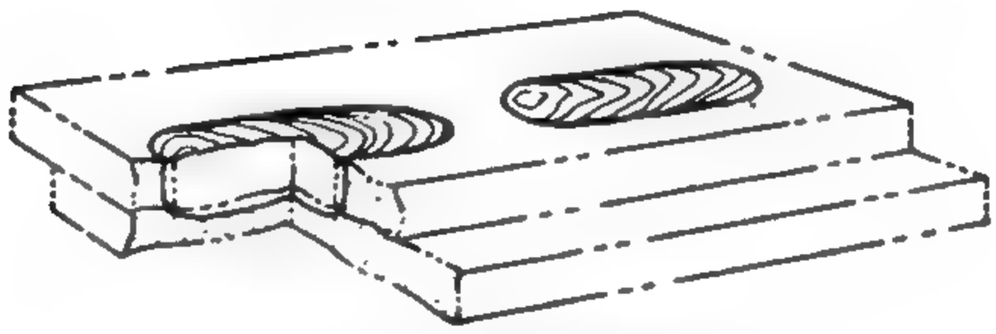
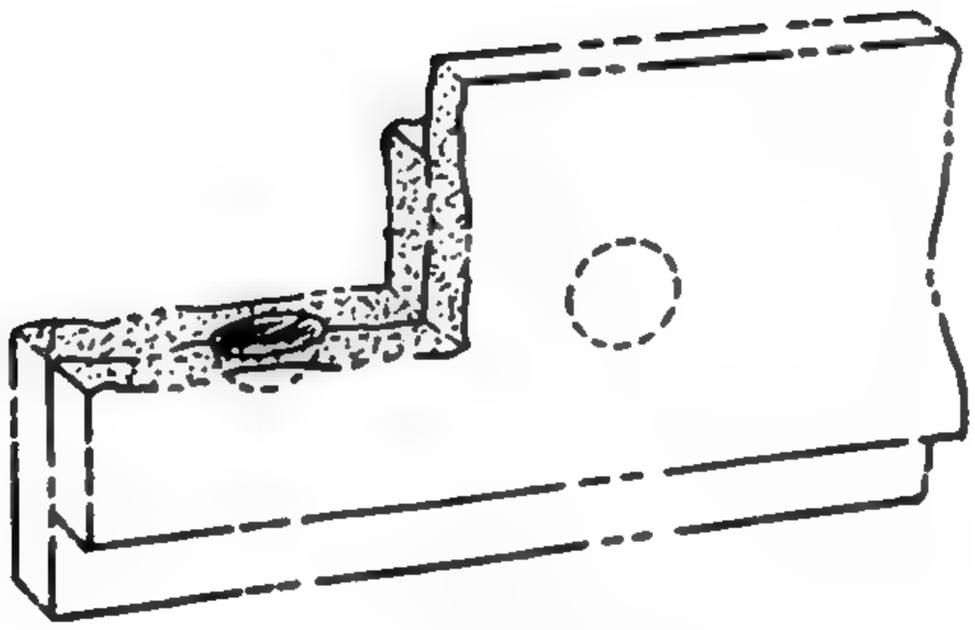
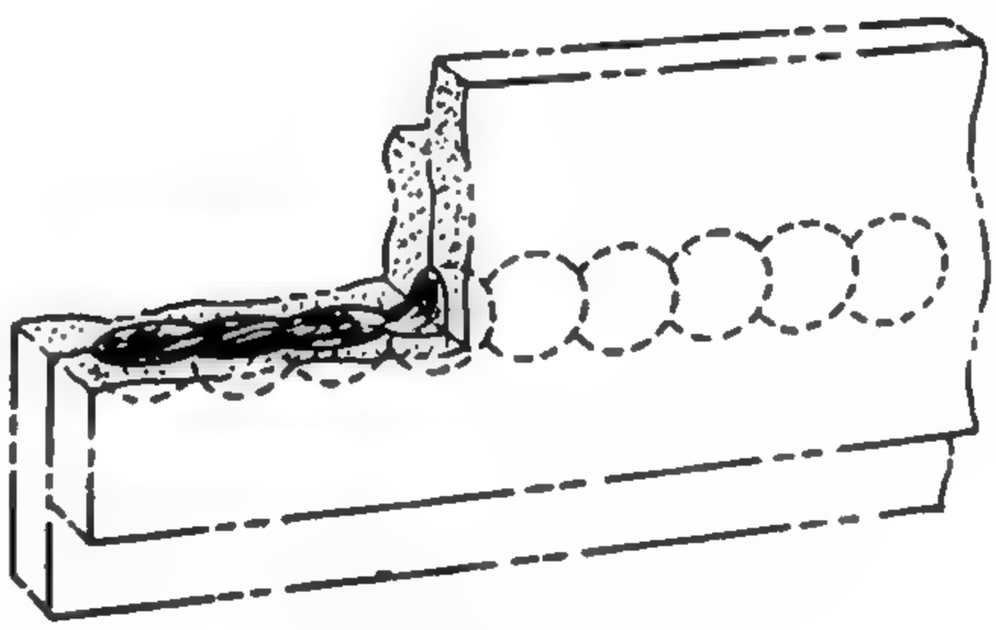


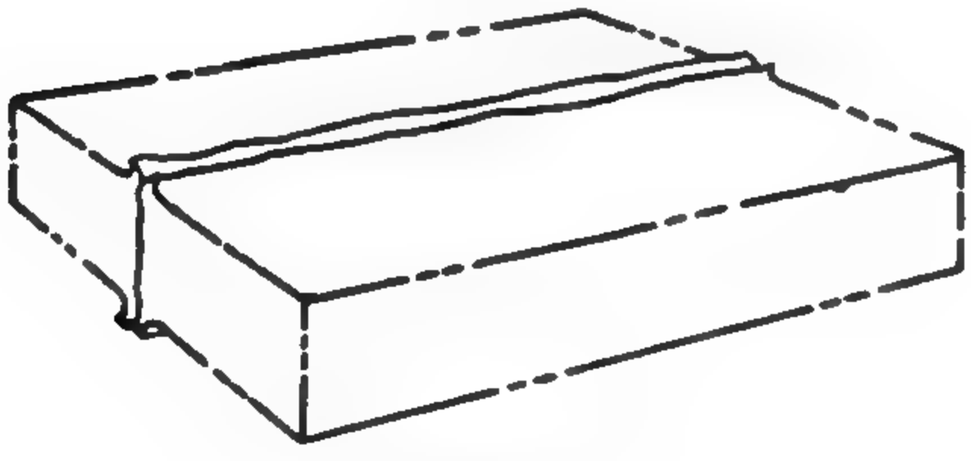
Fig. 15.—Slot Welds



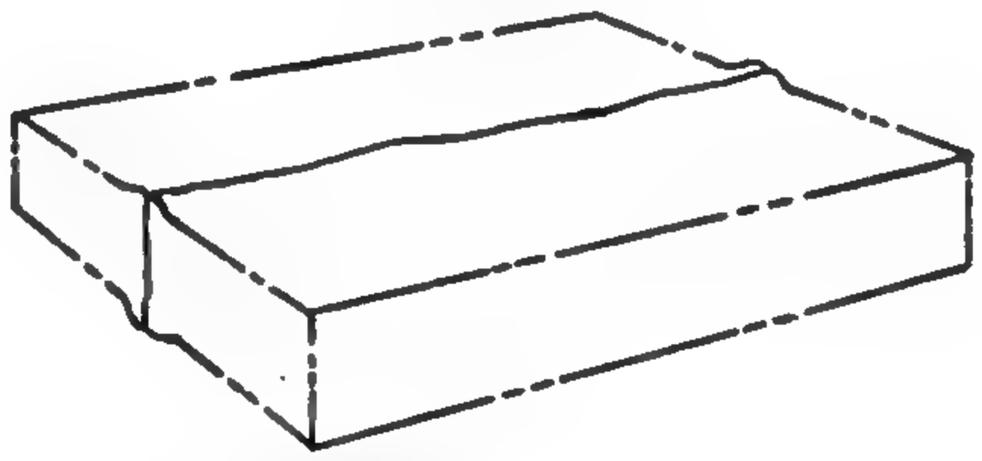
SPOT WELD



SEAM WELD

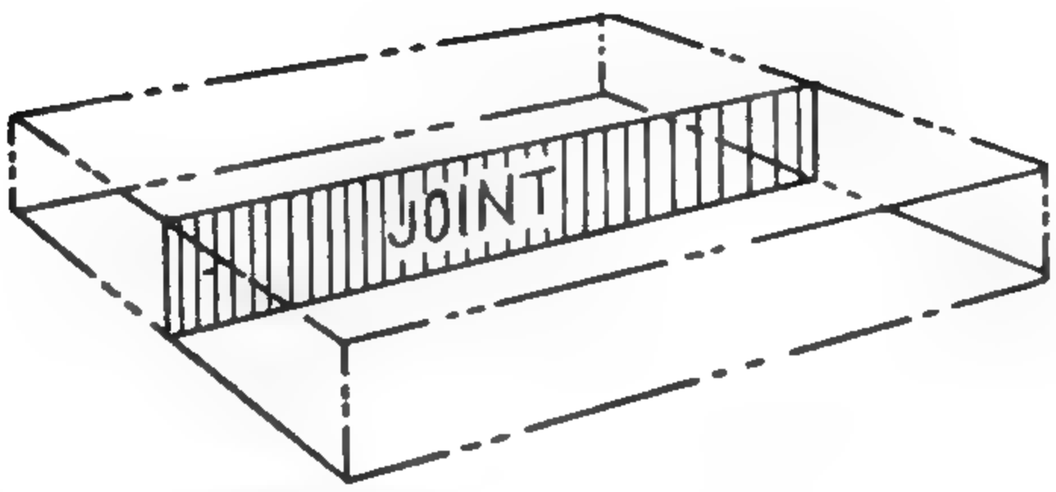


FLASH WELD



UPSET WELD

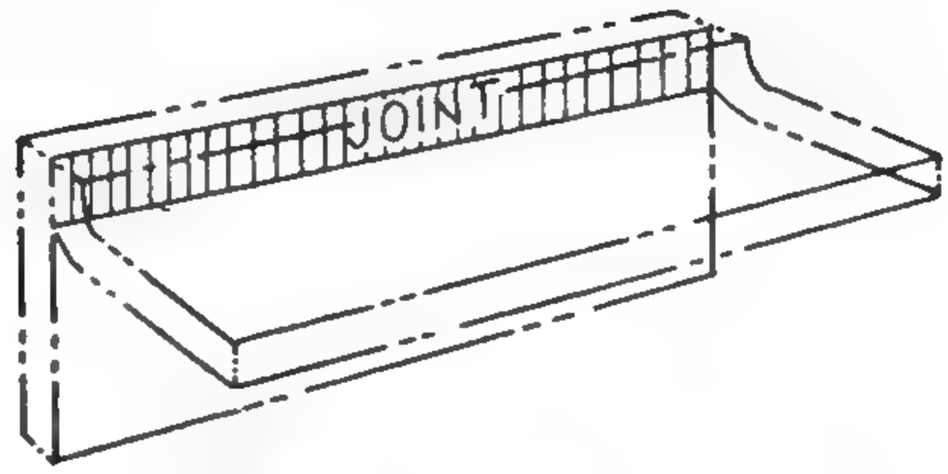
Fig. 16.—Types of Resistance Weld



BUTT JOINT

APPLICABLE WELDS

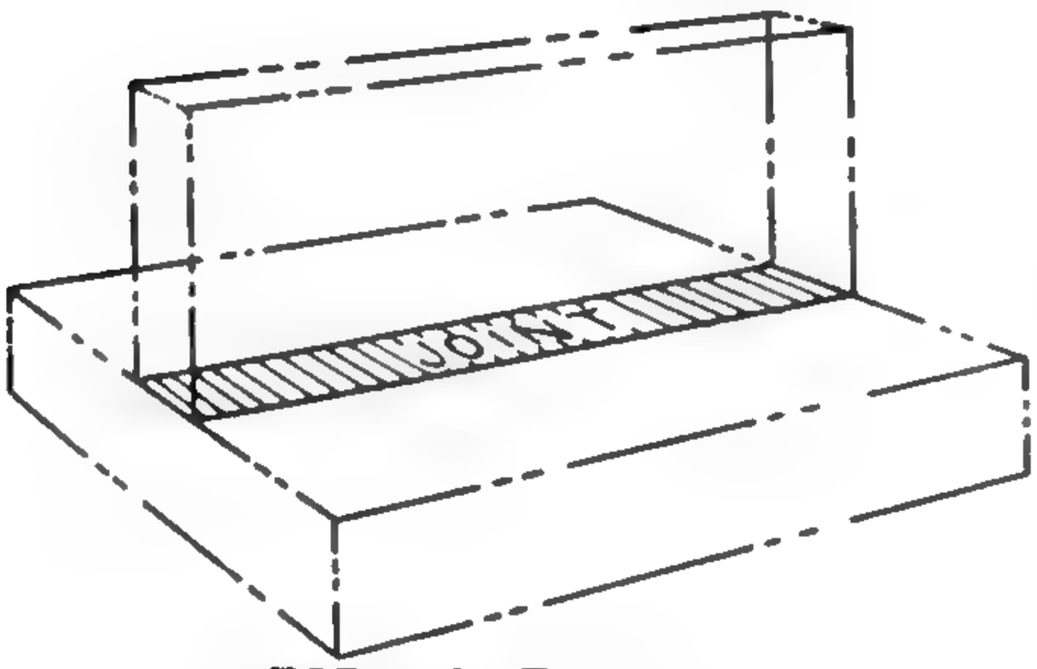
SQUARE-GROOVE	U-GROOVE
V-GROOVE	J-GROOVE
BEVEL-GROOVE	FLASH
UPSET	



EDGE JOINT

APPLICABLE WELDS

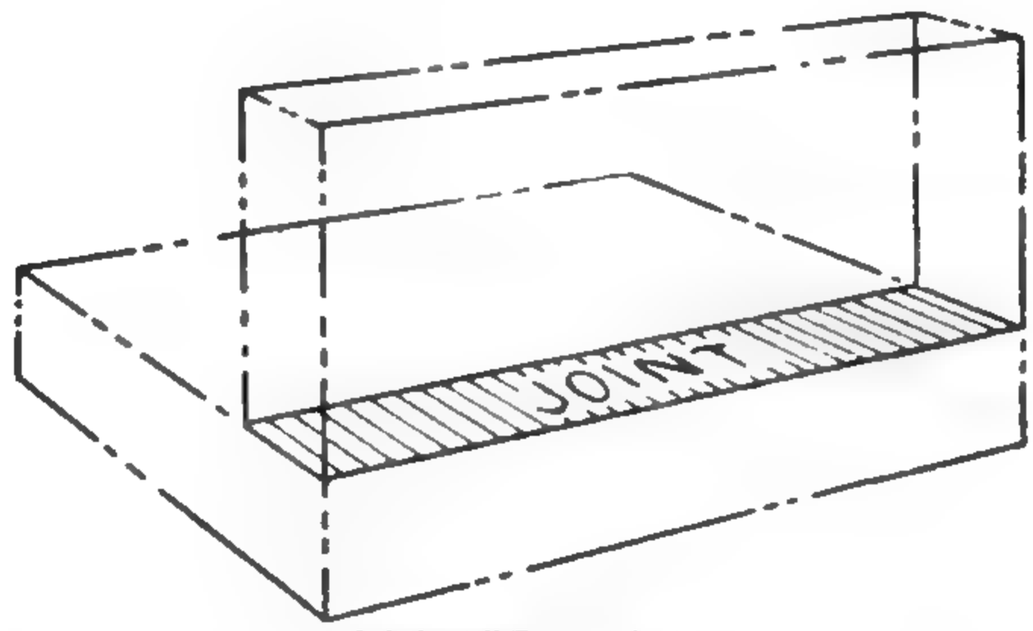
SQUARE-GROOVE	U-GROOVE
BEVEL-GROOVE	J-GROOVE
V-GROOVE	SPOT
SEAM	PROJECTION



TEE JOINT

APPLICABLE WELDS

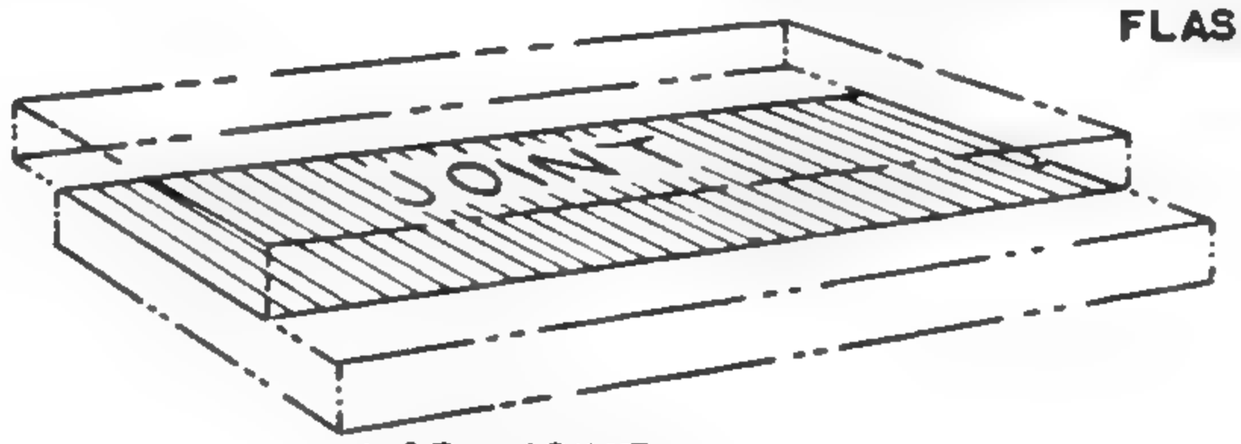
BEVEL-GROOVE	FILLET
J-GROOVE	SLOT
PLUG	



CORNER JOINT

APPLICABLE WELDS

SQUARE-GROOVE	U-GROOVE
V-GROOVE	J-GROOVE
BEVEL-GROOVE	FILLET
FLASH	



LAP JOINT

APPLICABLE WELDS

FILLET	PLUG
BEVEL-GROOVE	SPOT
SLOT	PROJECTION
J-GROOVE	SEAM

Fig. 17.—Types of Joint

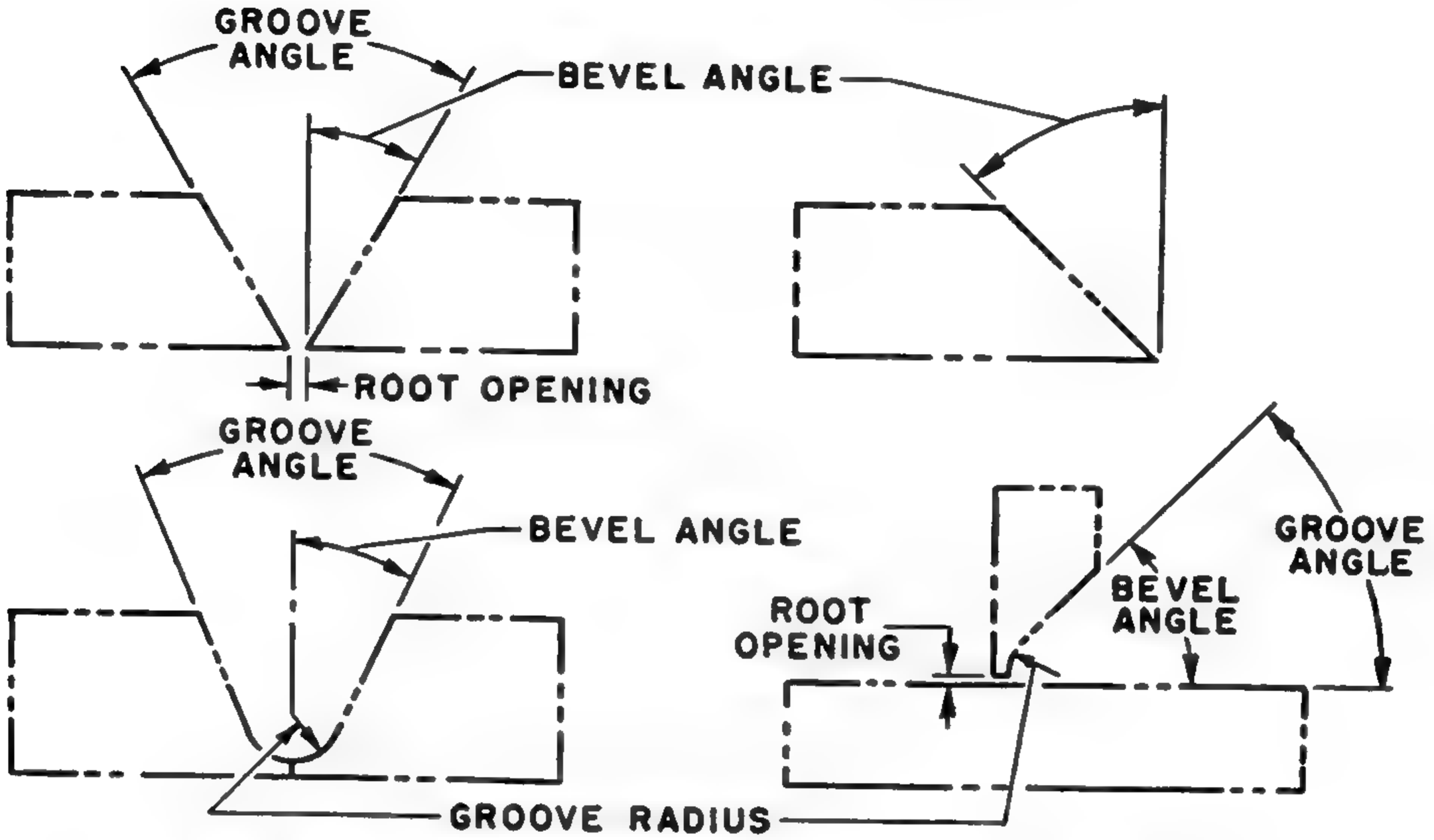


Fig. 18.—Bevel Angle, Groove Angle, Groove Radius and Root Opening

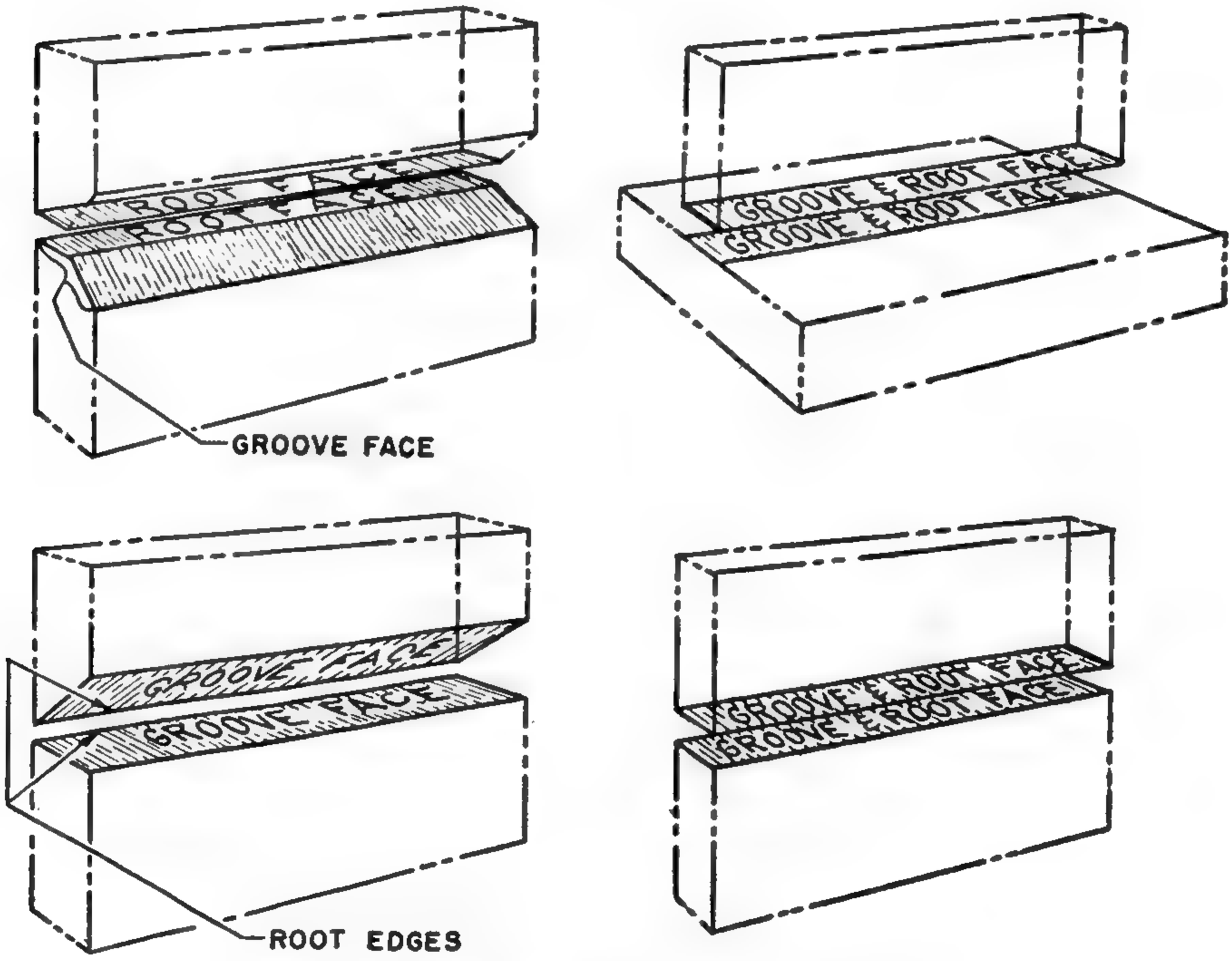


Fig. 19. Groove Face, Root Face and Root Edge

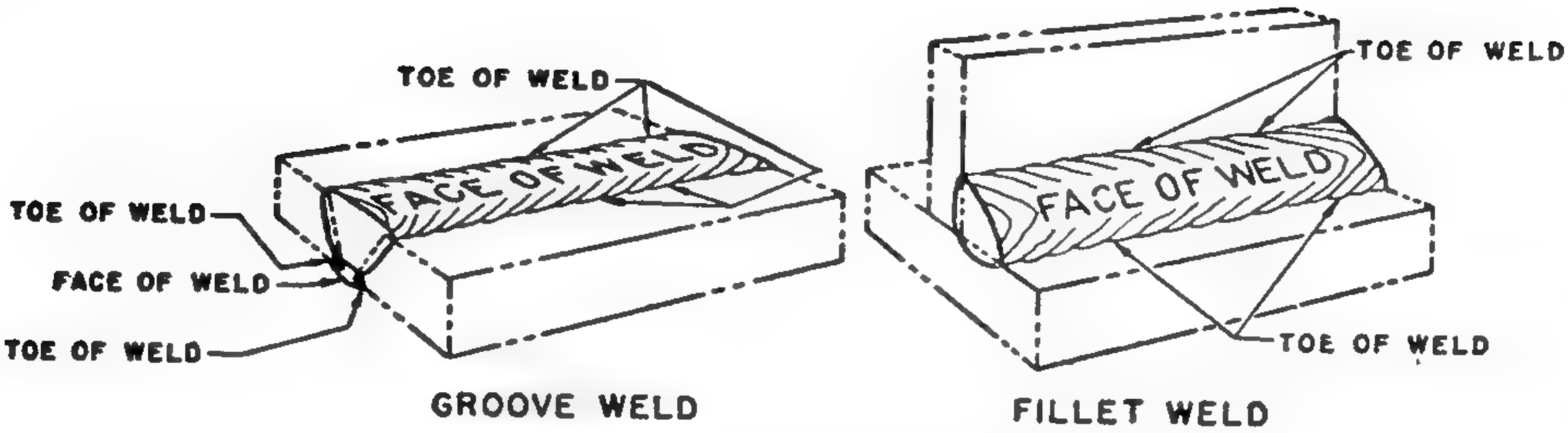


Fig. 20.—Face and Toe of Weld

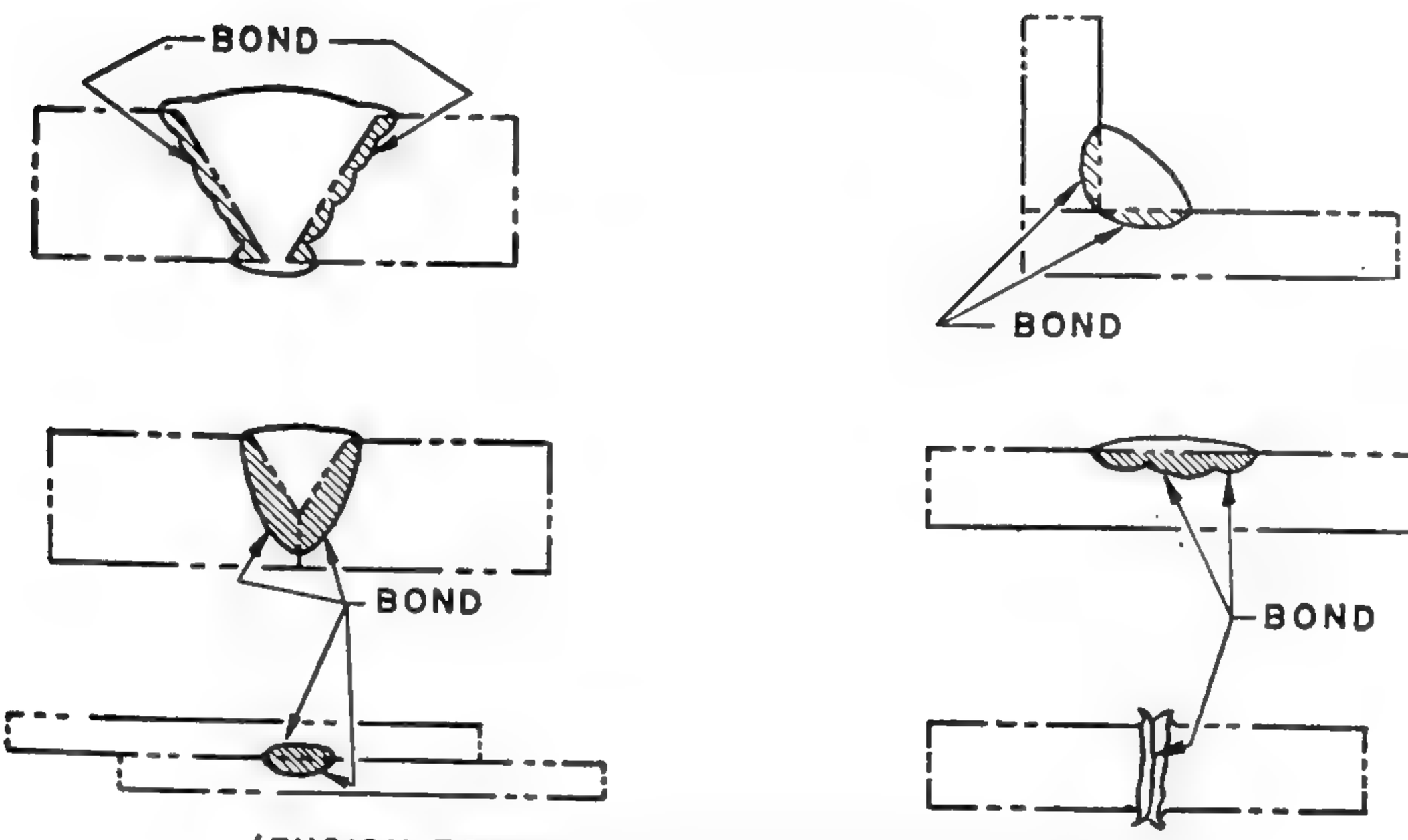


Fig. 21.—Bond and Fusion Zone

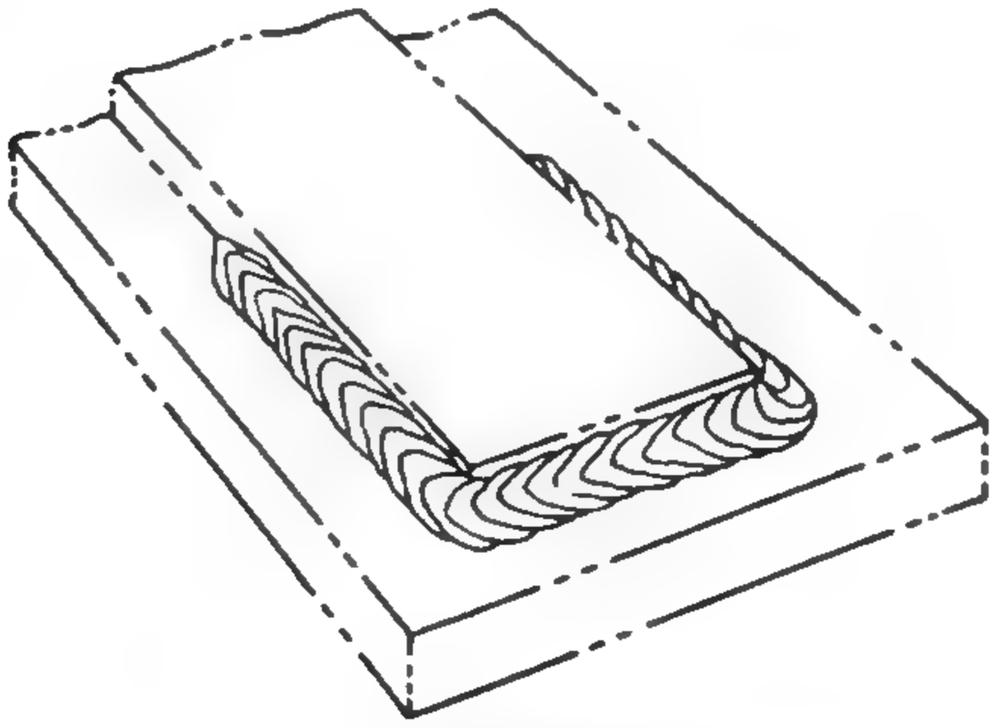


Fig. 22.—Boxing

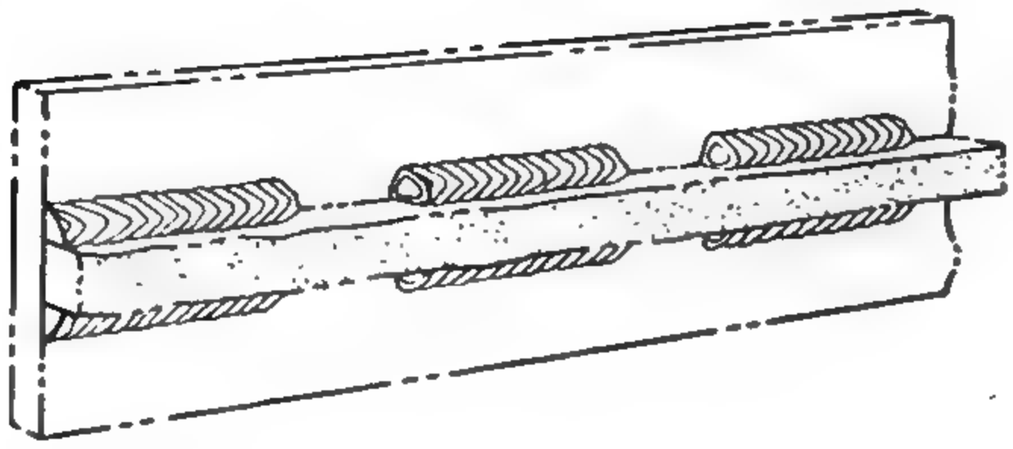


Fig. 23.—Chain Intermittent Fillet Welding

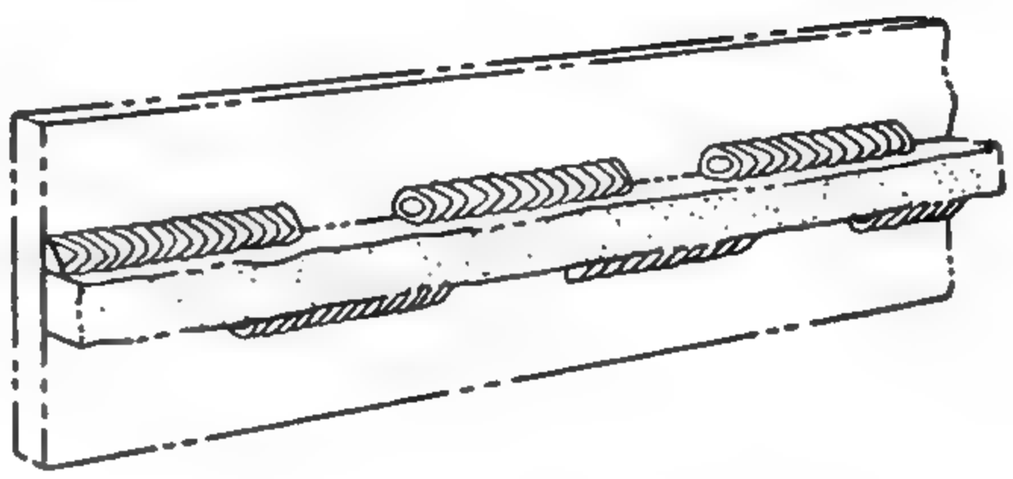


Fig. 24.—Staggered Intermittent Fillet Welding

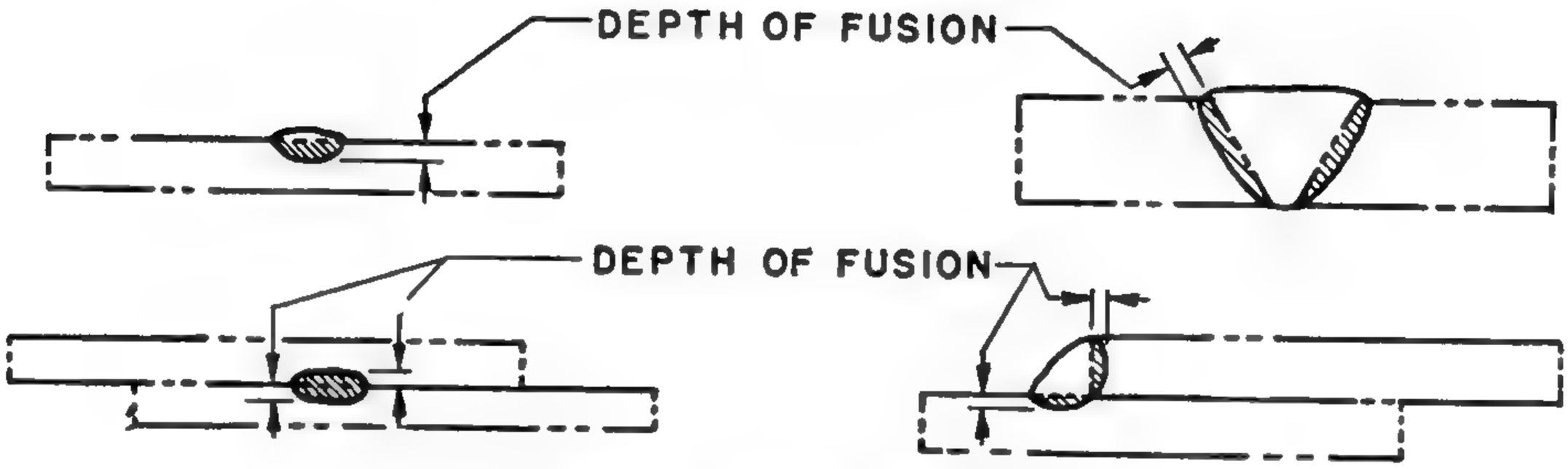


Fig. 25.—Depth of Fusion

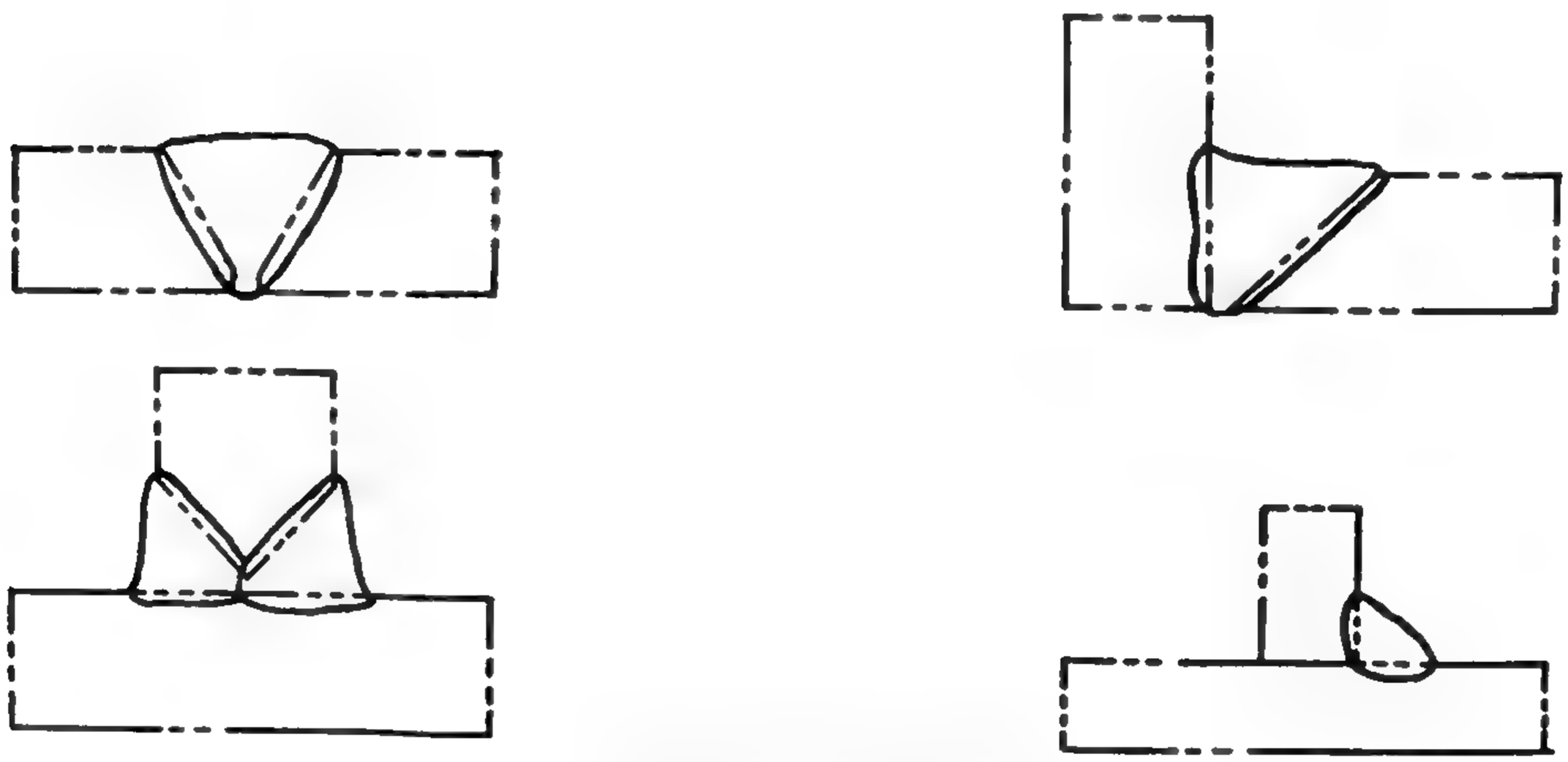


Fig. 26.—Complete Fusion

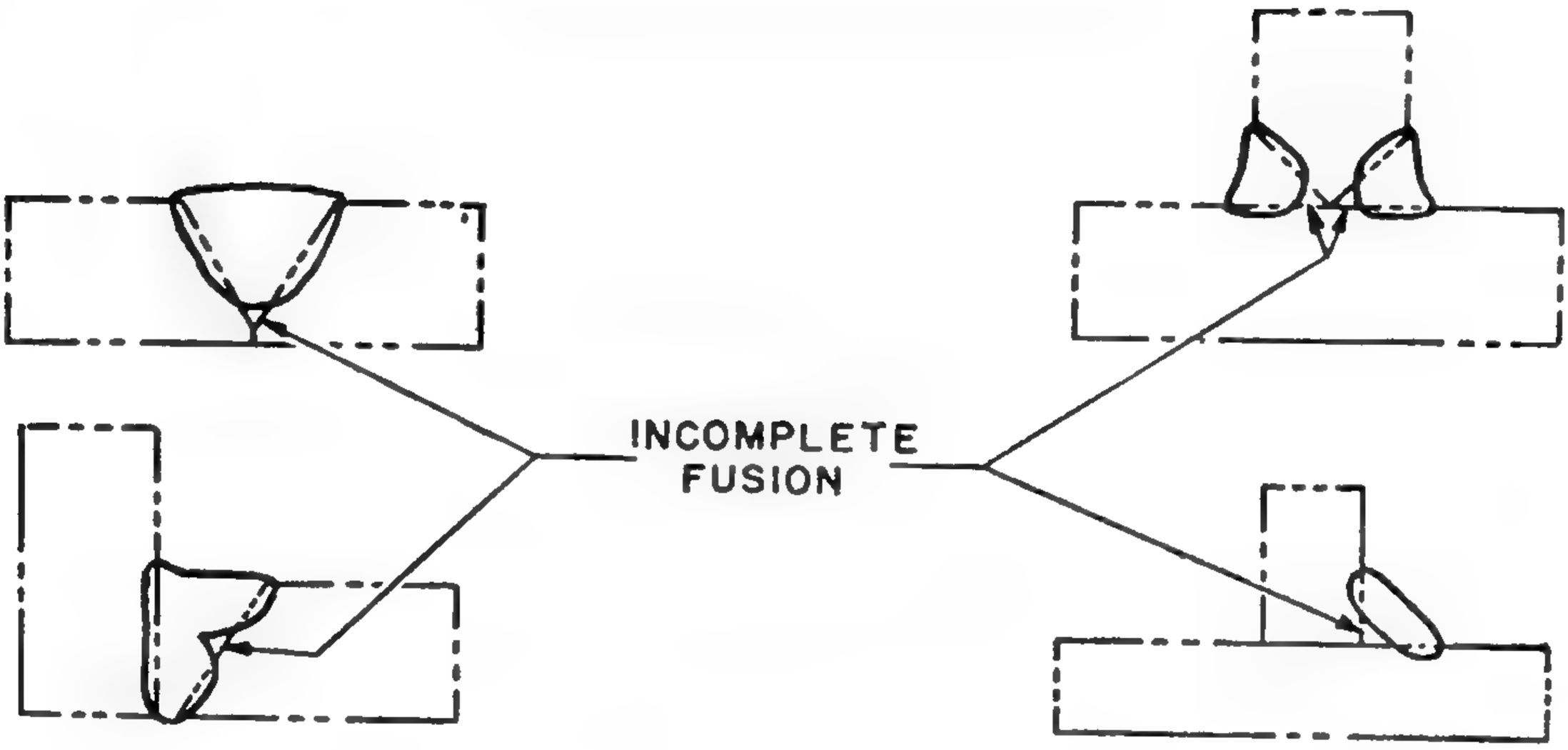


Fig. 27.—Incomplete Fusion

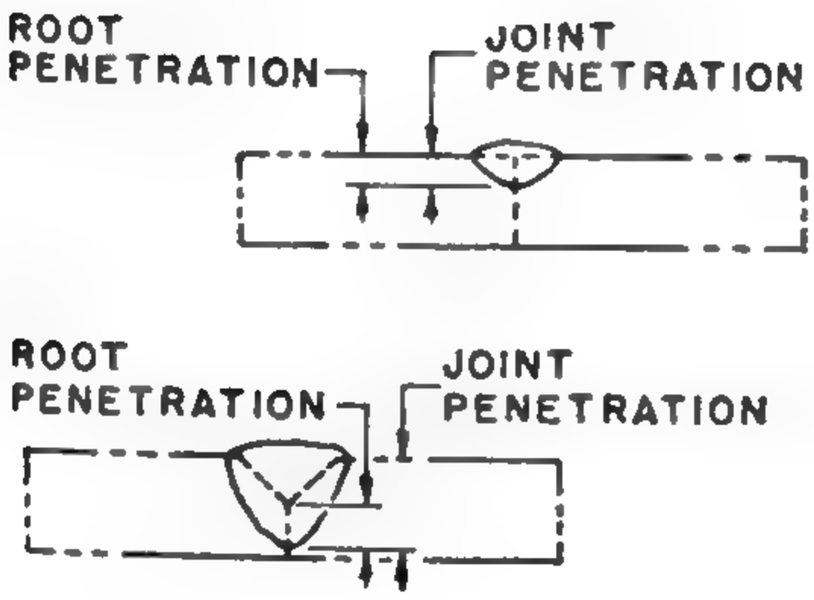


Fig. 28.—Root Penetration and Joint Penetration of Groove Welds

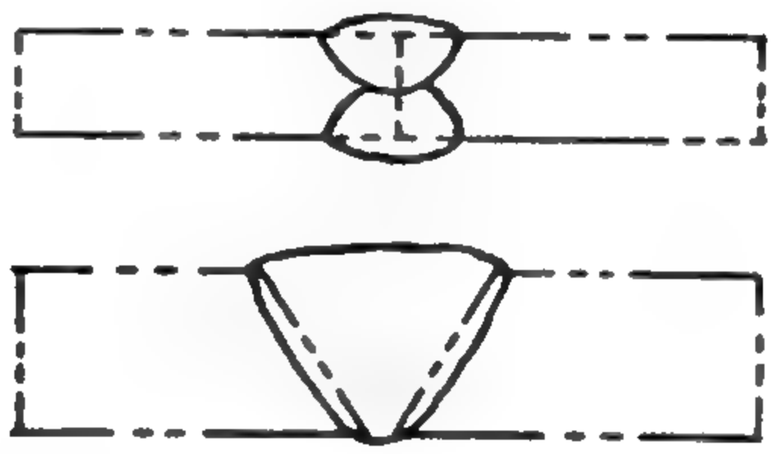


Fig. 29.—Complete Joint Penetration

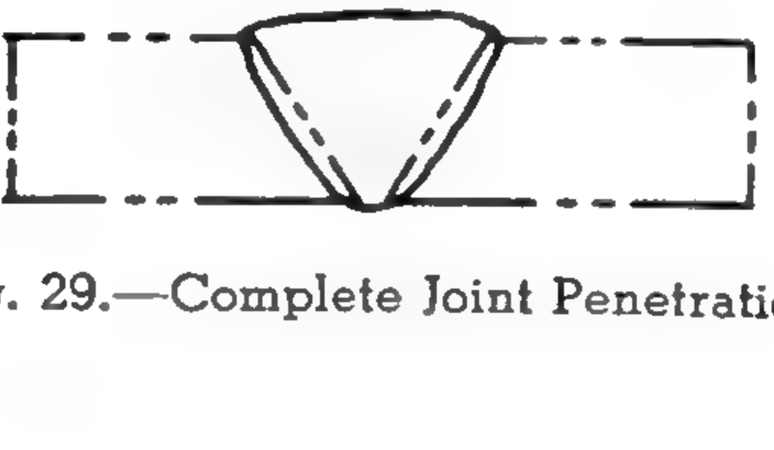


Fig. 30.—Partial Joint Penetration

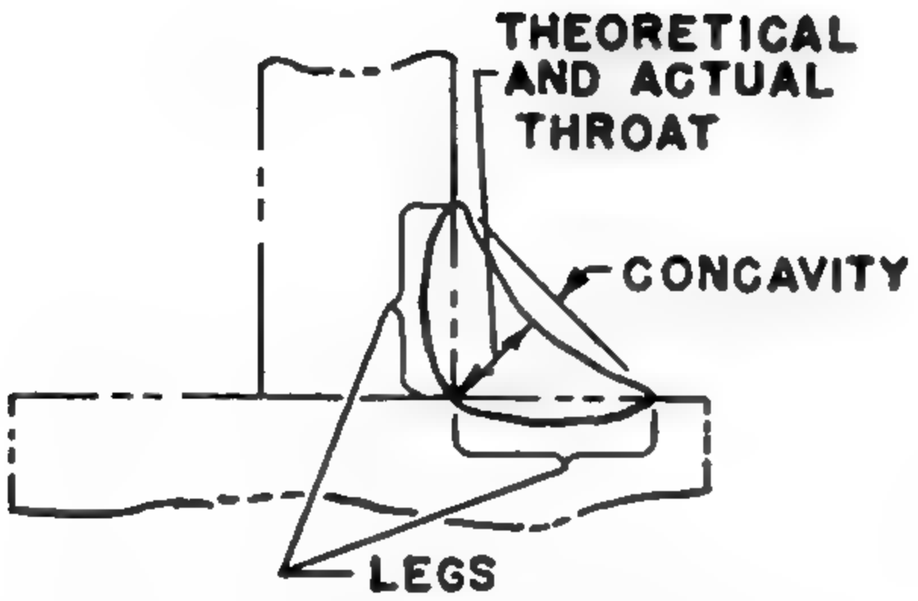


Fig. 31.—Concave Fillet Weld

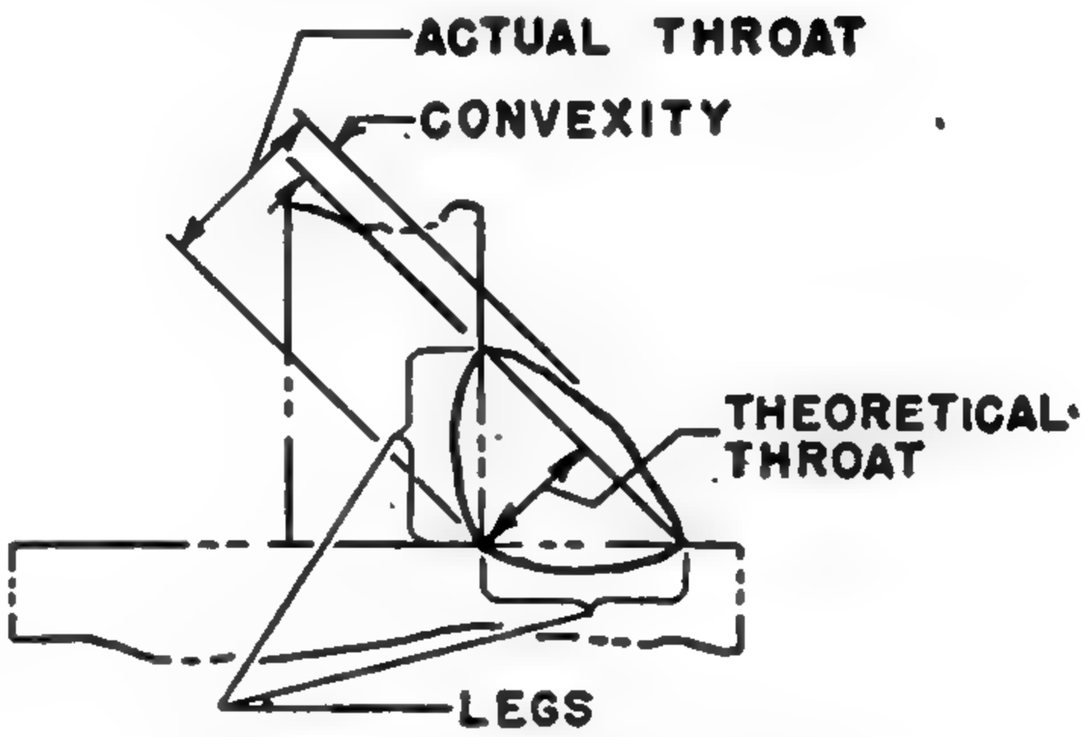


Fig. 32.—Convex Fillet Weld

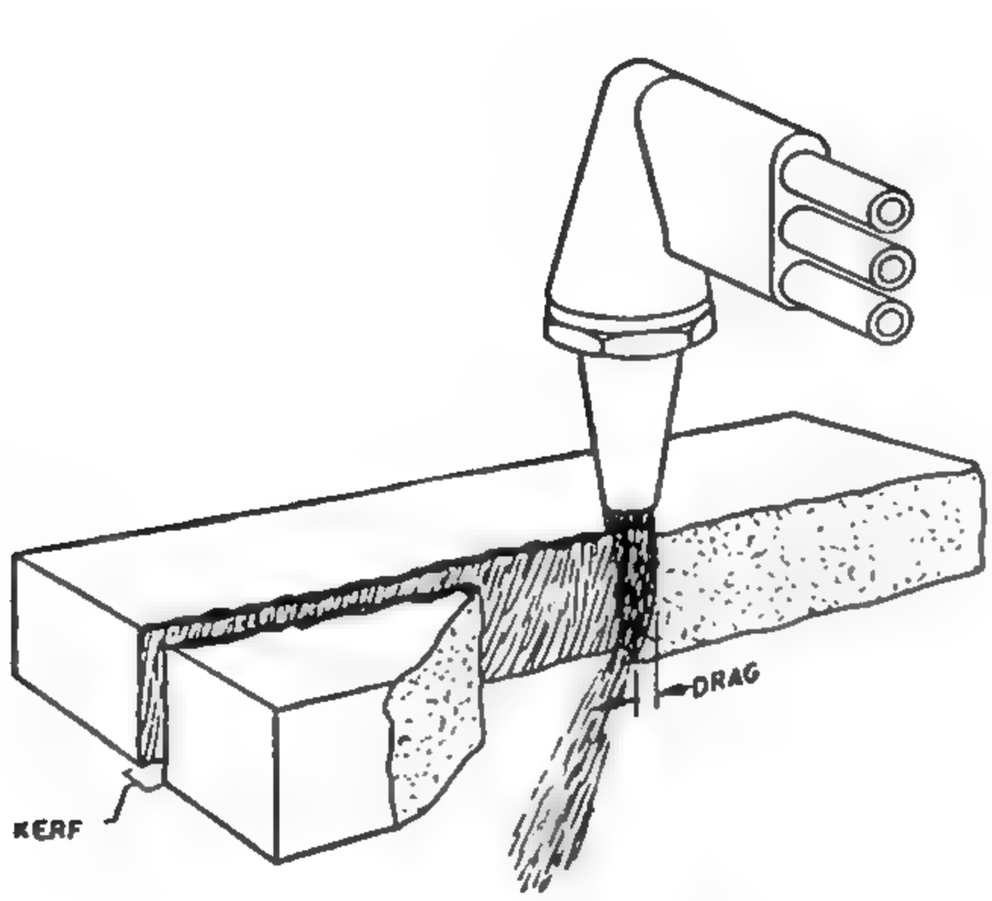


Fig. 33.—Drag and Kerf

Fig. 34.—Reverse Polarity

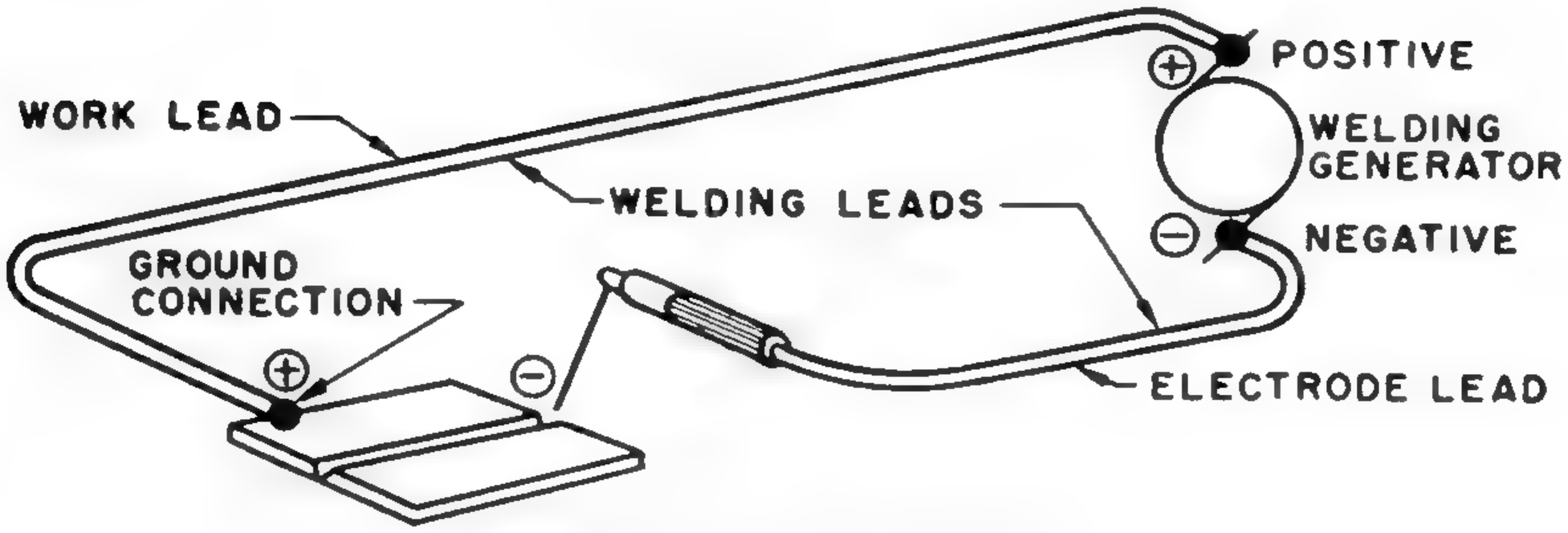


Fig. 35.—Straight Polarity

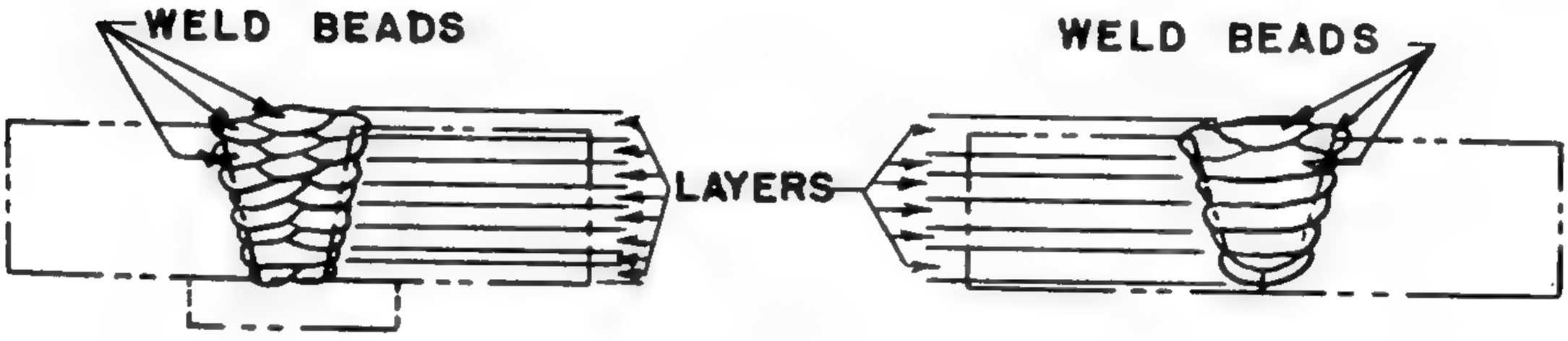


Fig. 36.—Weld Beads and Layers

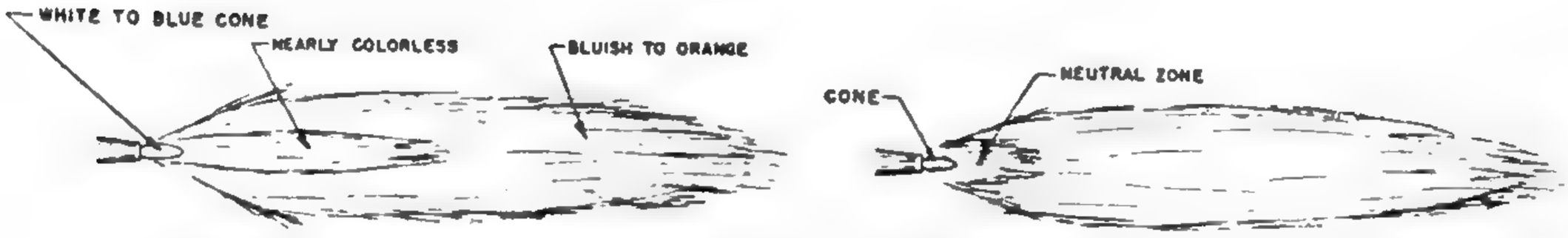


Fig. 37.—Neutral Flame

Fig. 38.—Oxidizing Flame

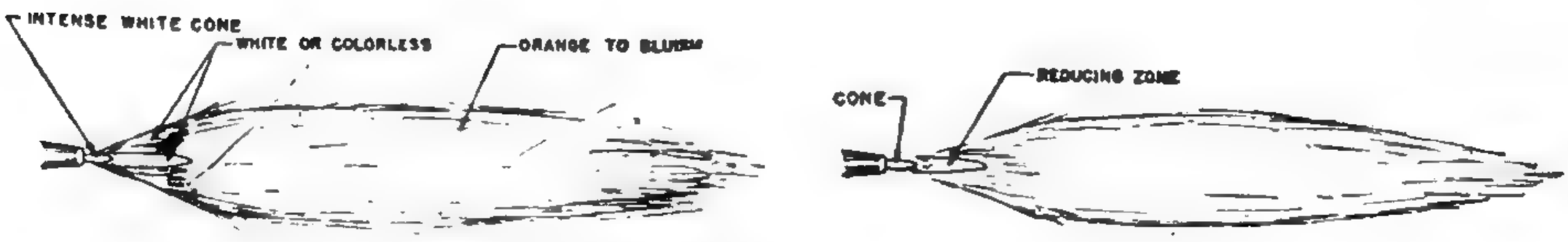


Fig. 39.—Reducing Flame

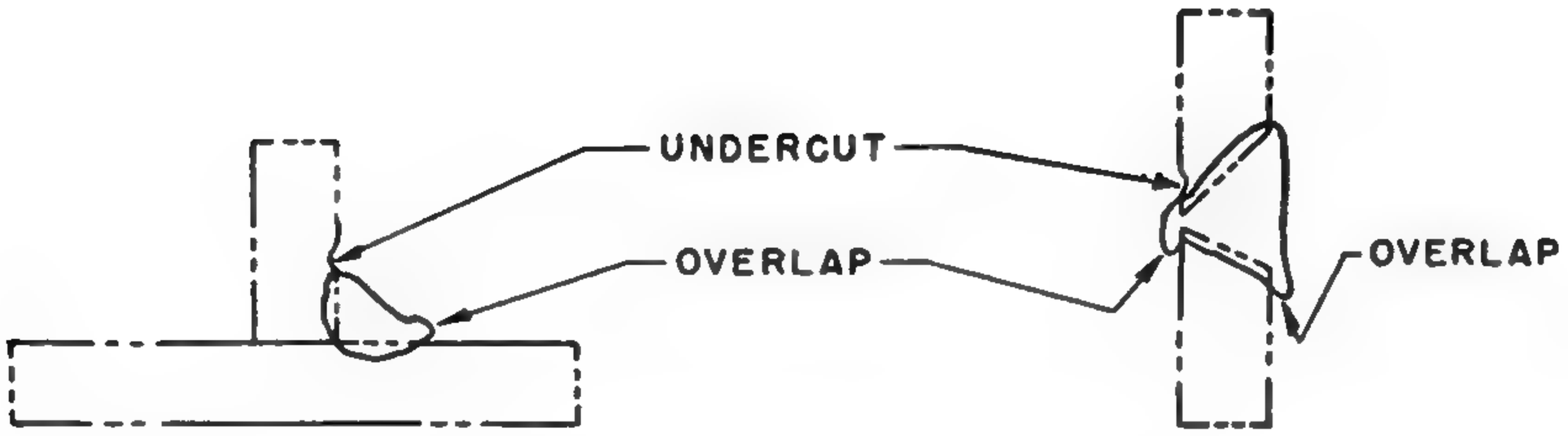


Fig. 40.—Undercut and Overlap

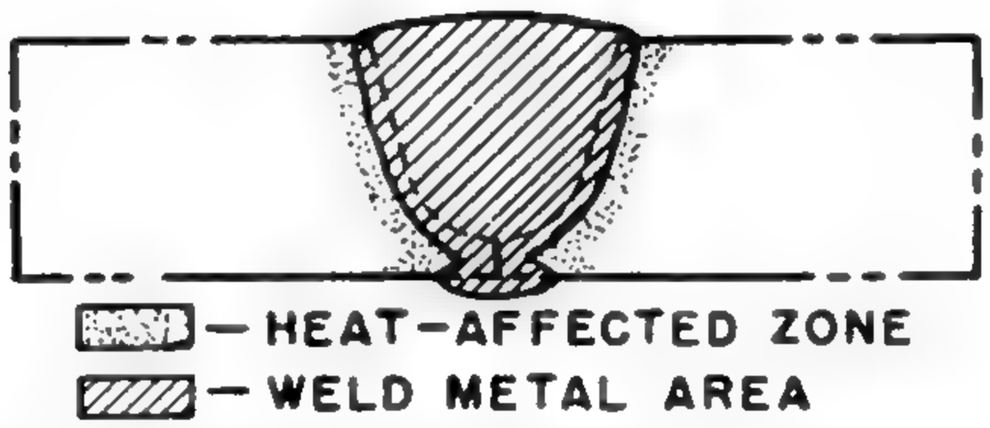


Fig. 41.—Heat-Affected Zone and Weld Metal Area

Fig. 42.—Reinforcement

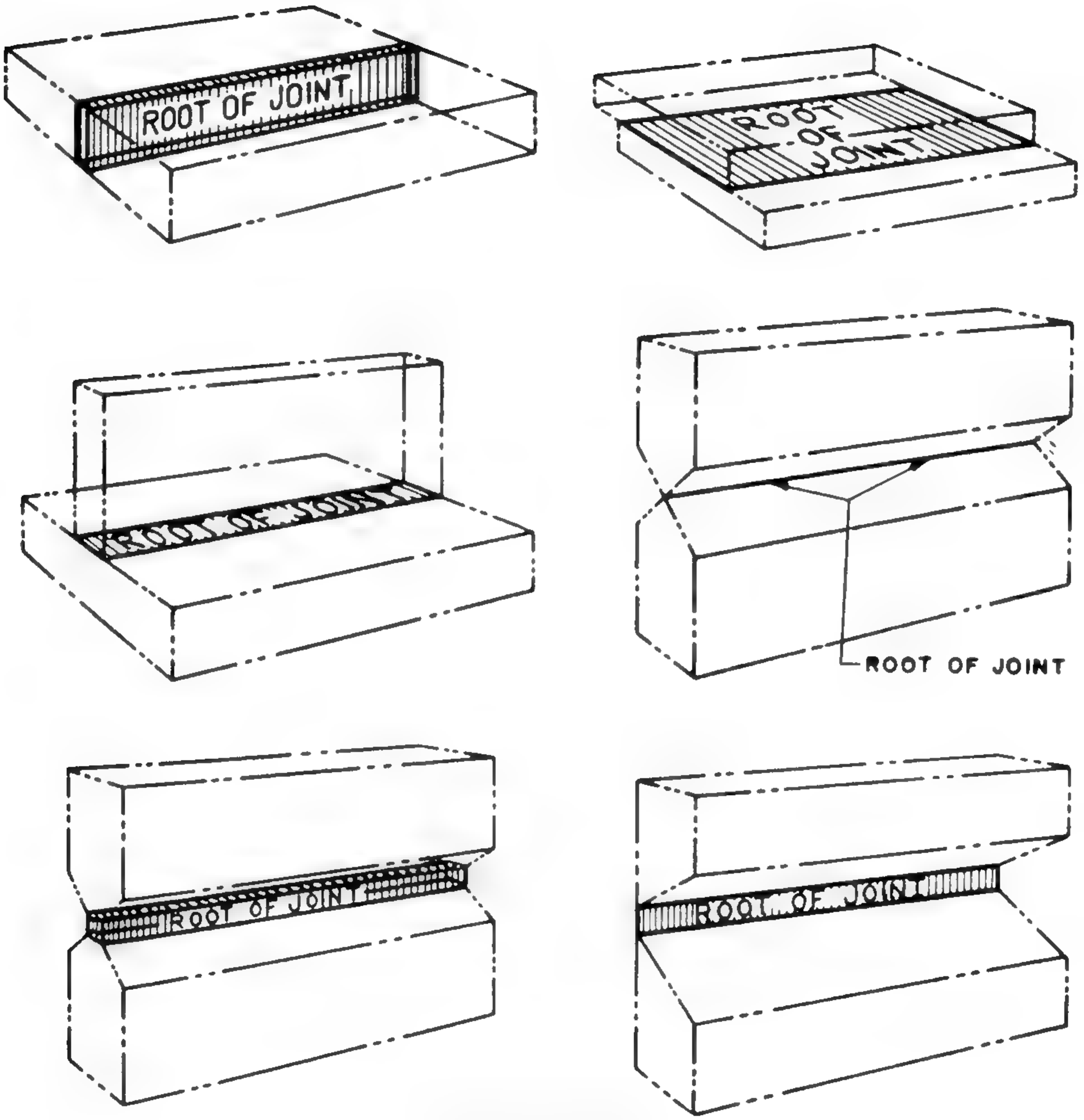


Fig. 43.—Root of Joint

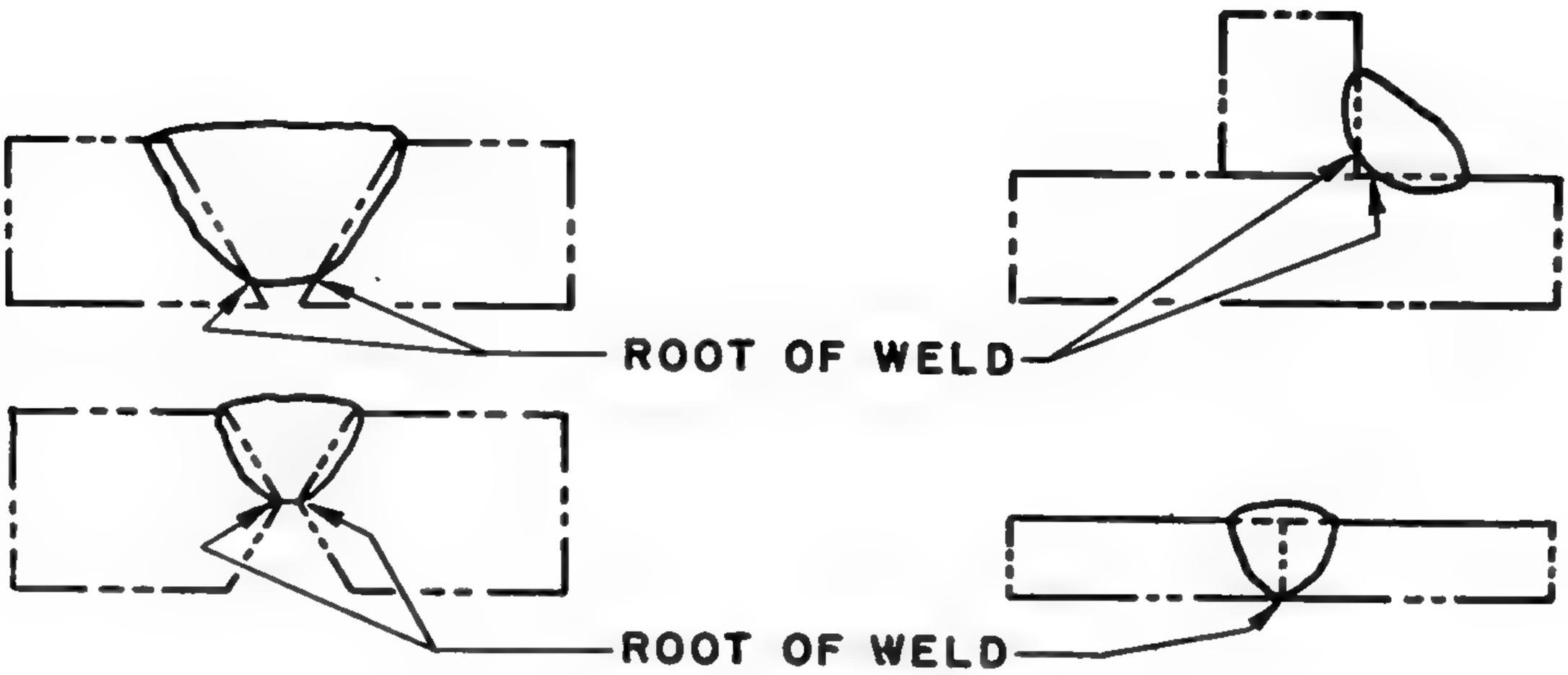


Fig. 44.—Root of Weld

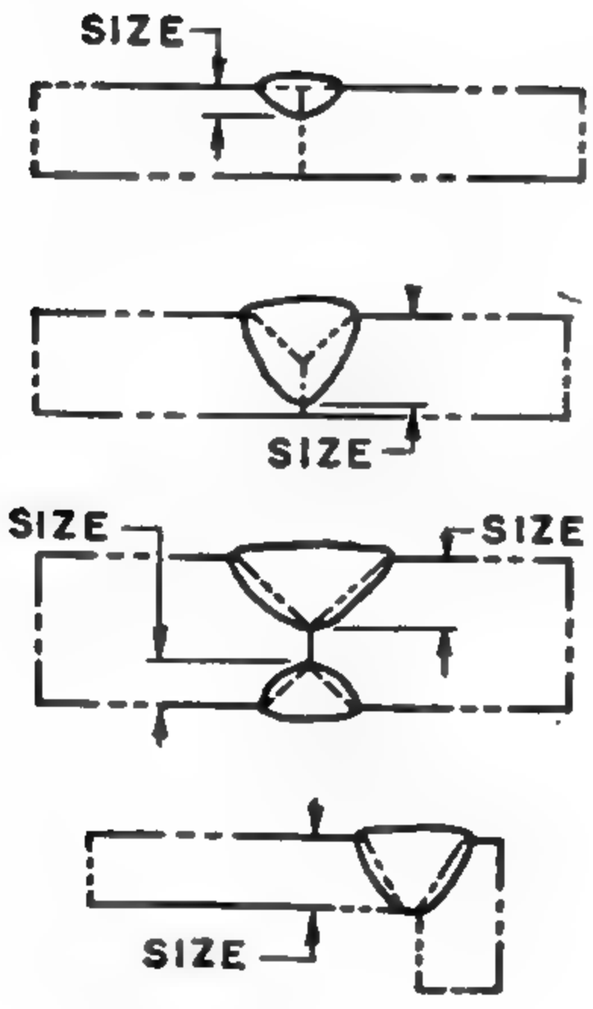


Fig. 45.—Size of Groove Welds

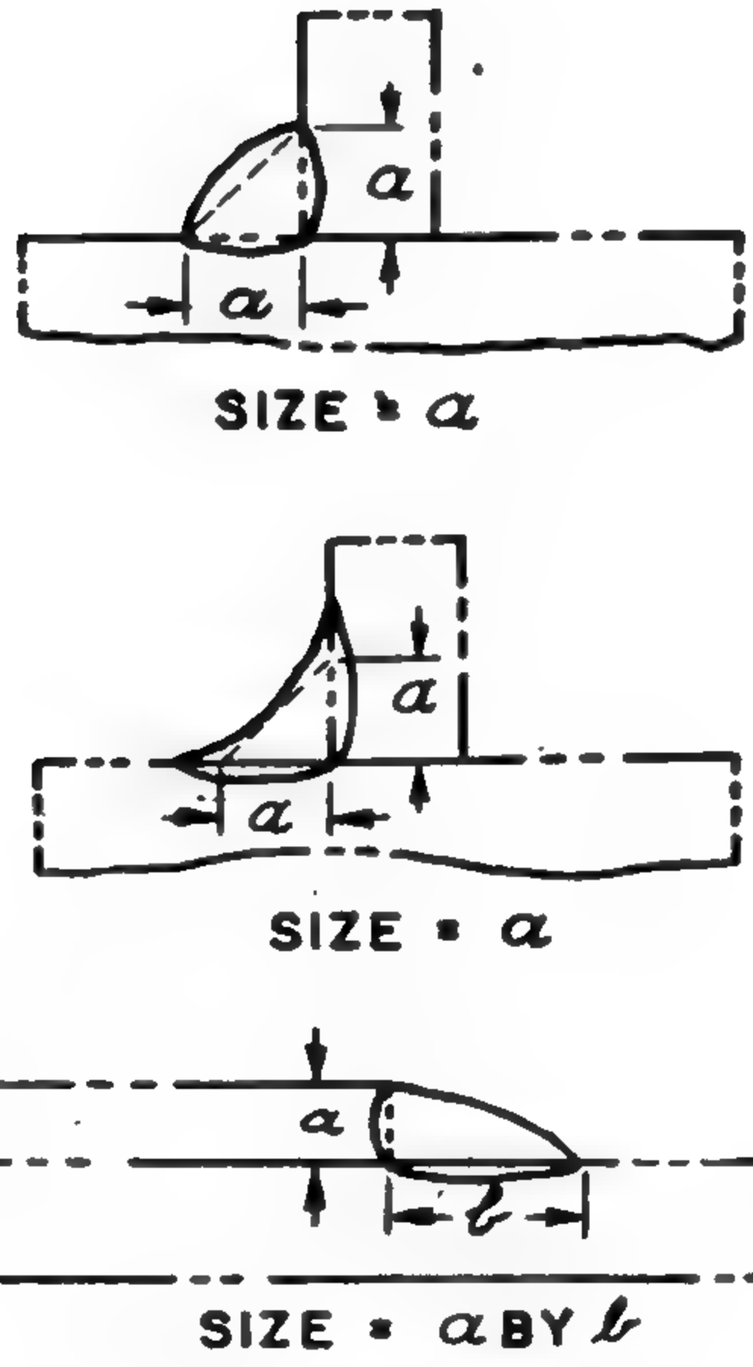


Fig. 46.—Size of Fillet Welds

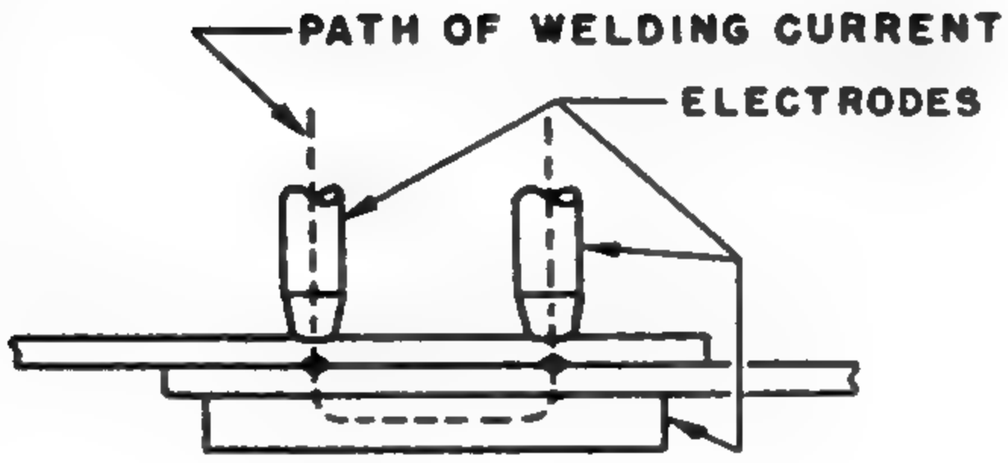


Fig. 47.—Series Welding

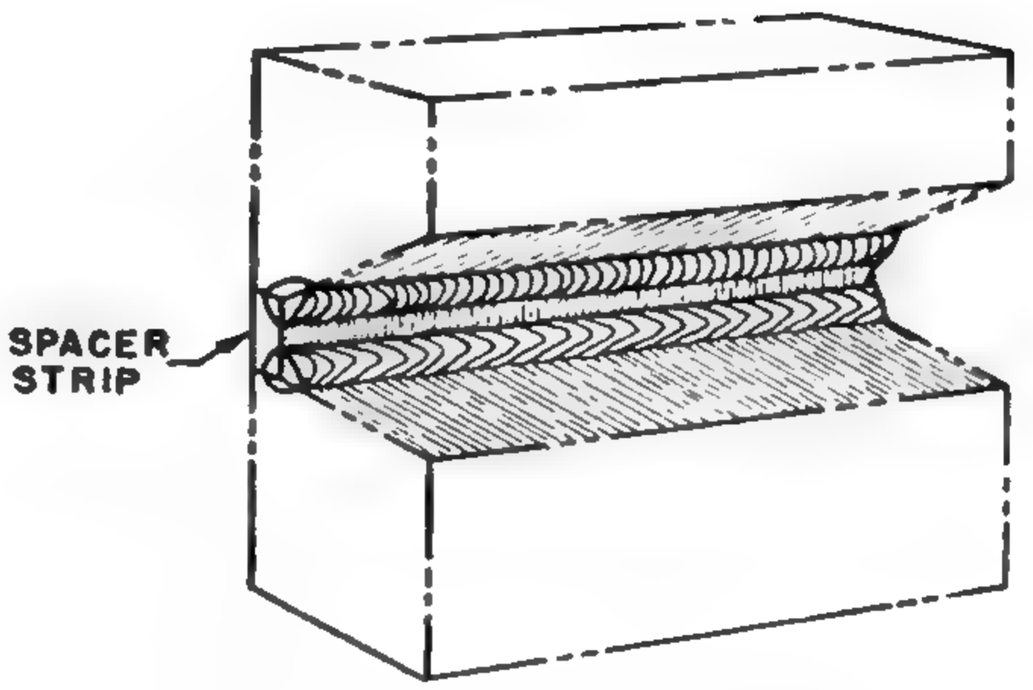


Fig. 48.—Spacer Strip

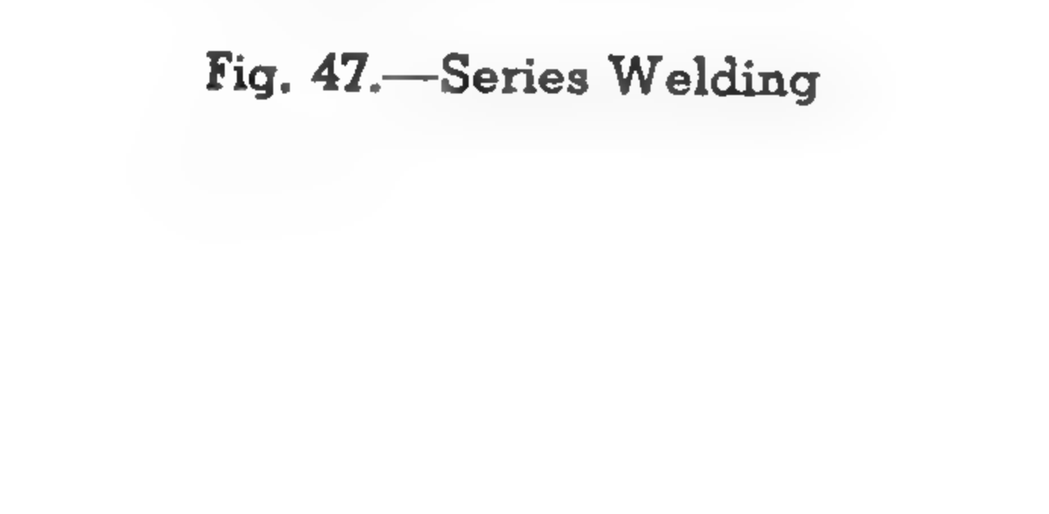


Fig. 49.—String Bead

Fig. 50.—Weave Bead

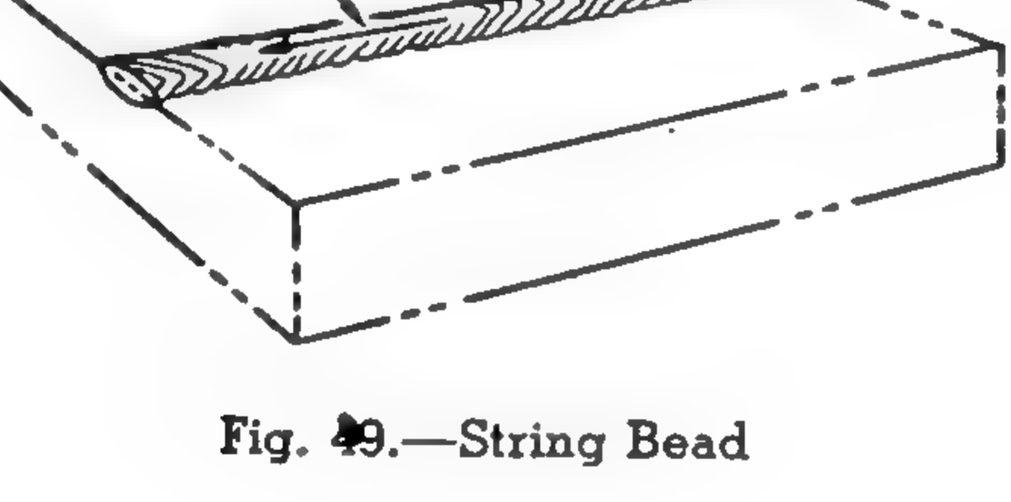


Fig. 51.—Toe Cracks

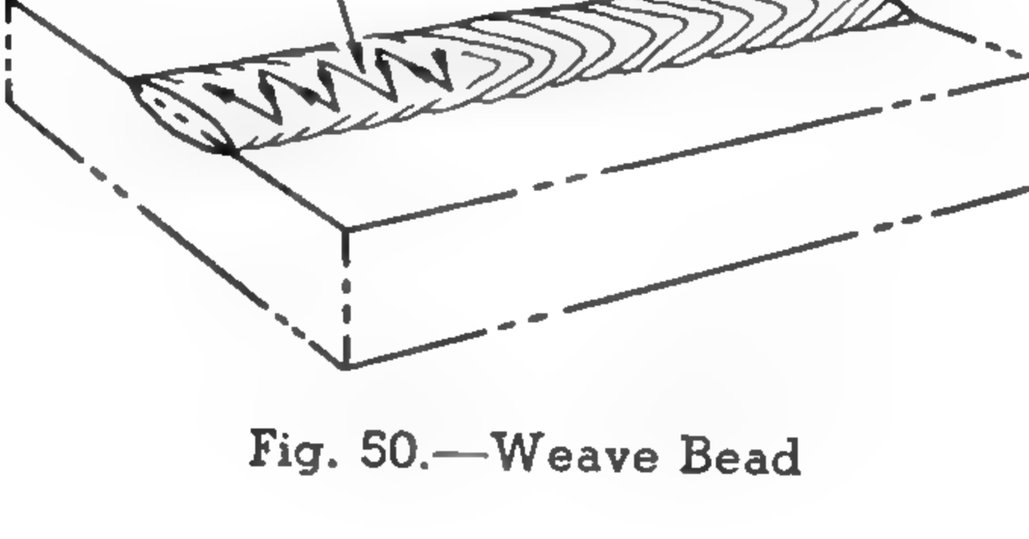


Fig. 52.—Underbead Cracks

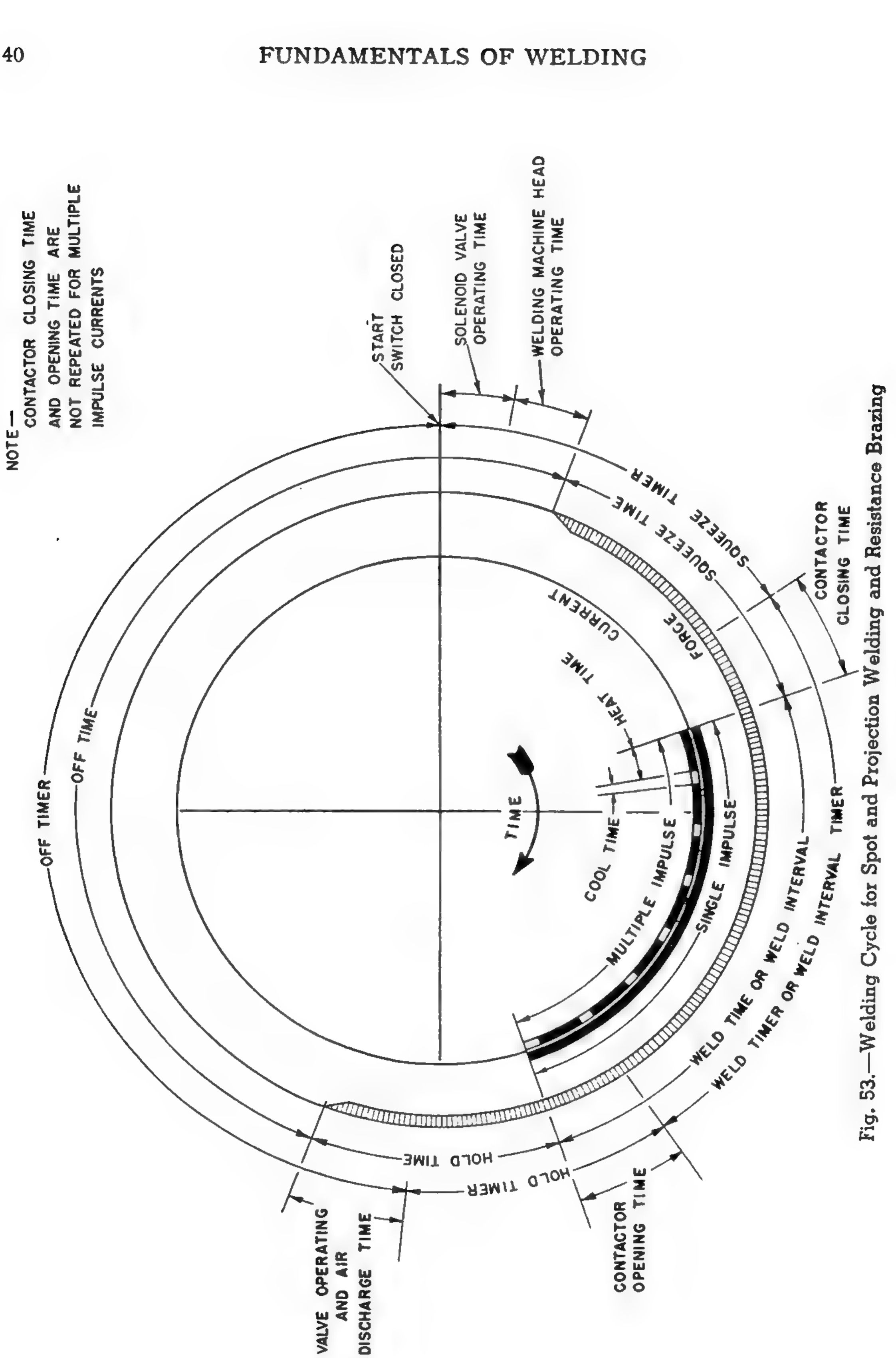


Fig. 53.—Welding Cycle for Spot and Projection Welding and Resistance Brazing

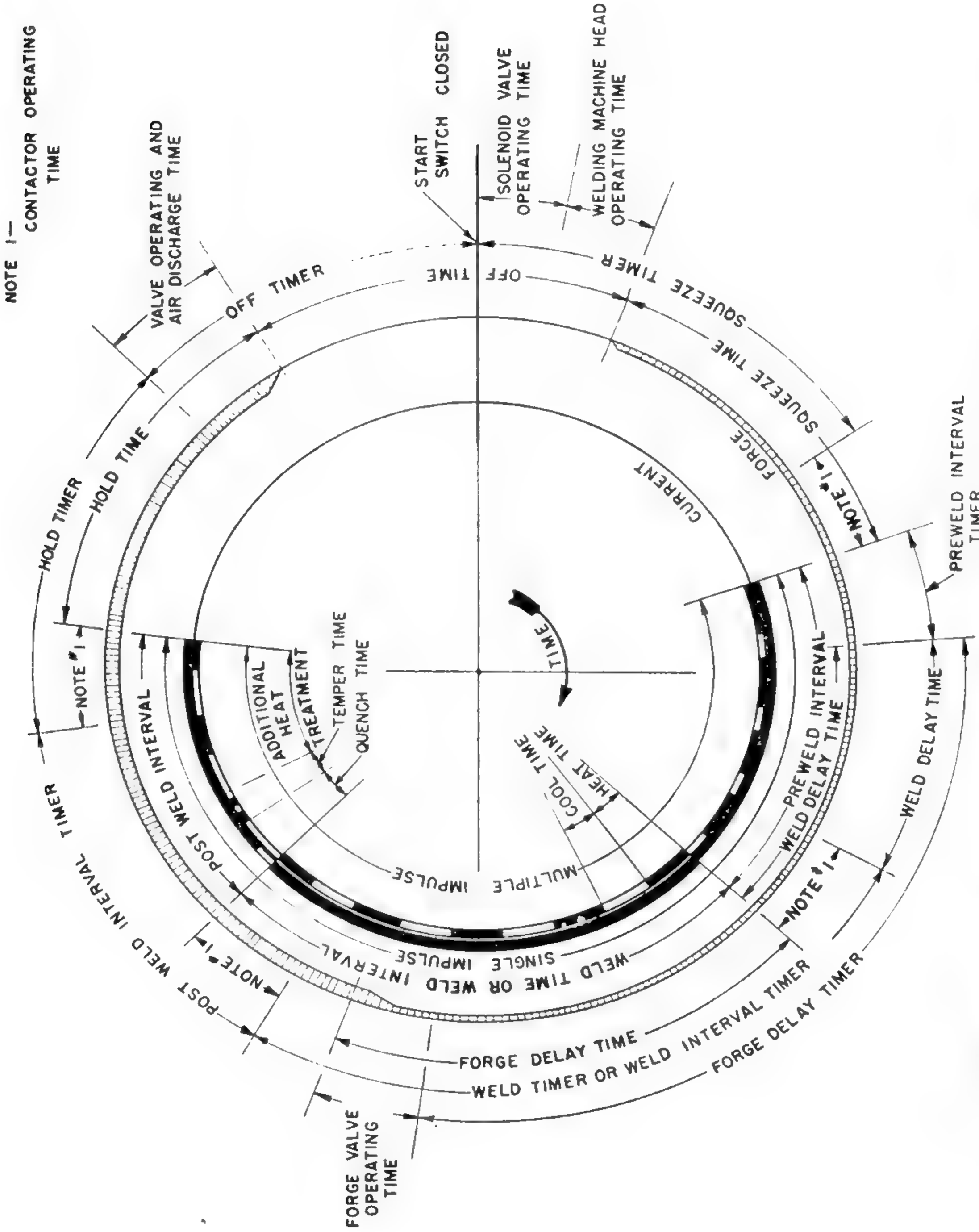


Fig. 54.—Welding Cycle for Spot and Projection Welding Including Preweld and Postweld Conditioning

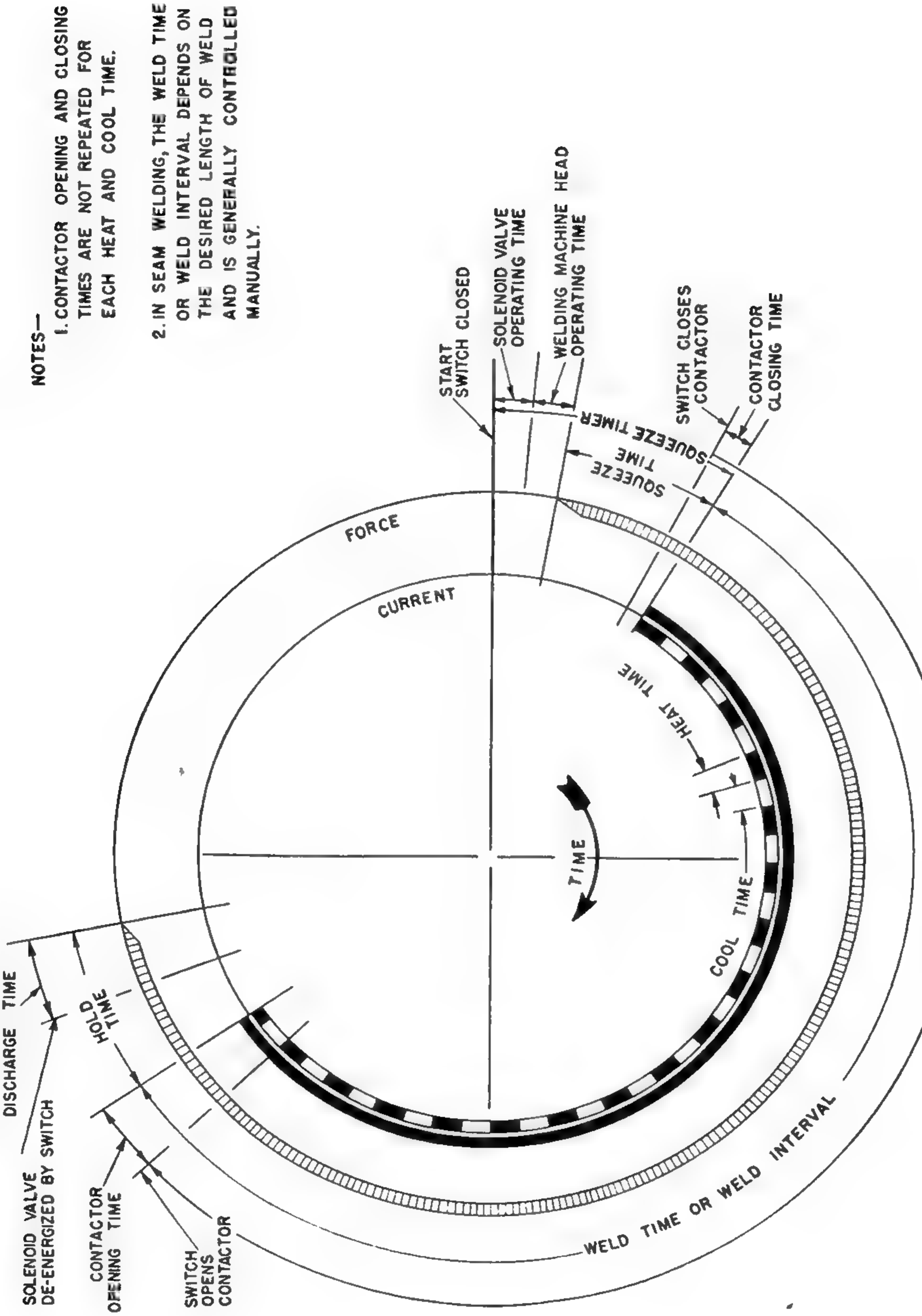


Fig. 55.—Welding Cycle for Seam Welding

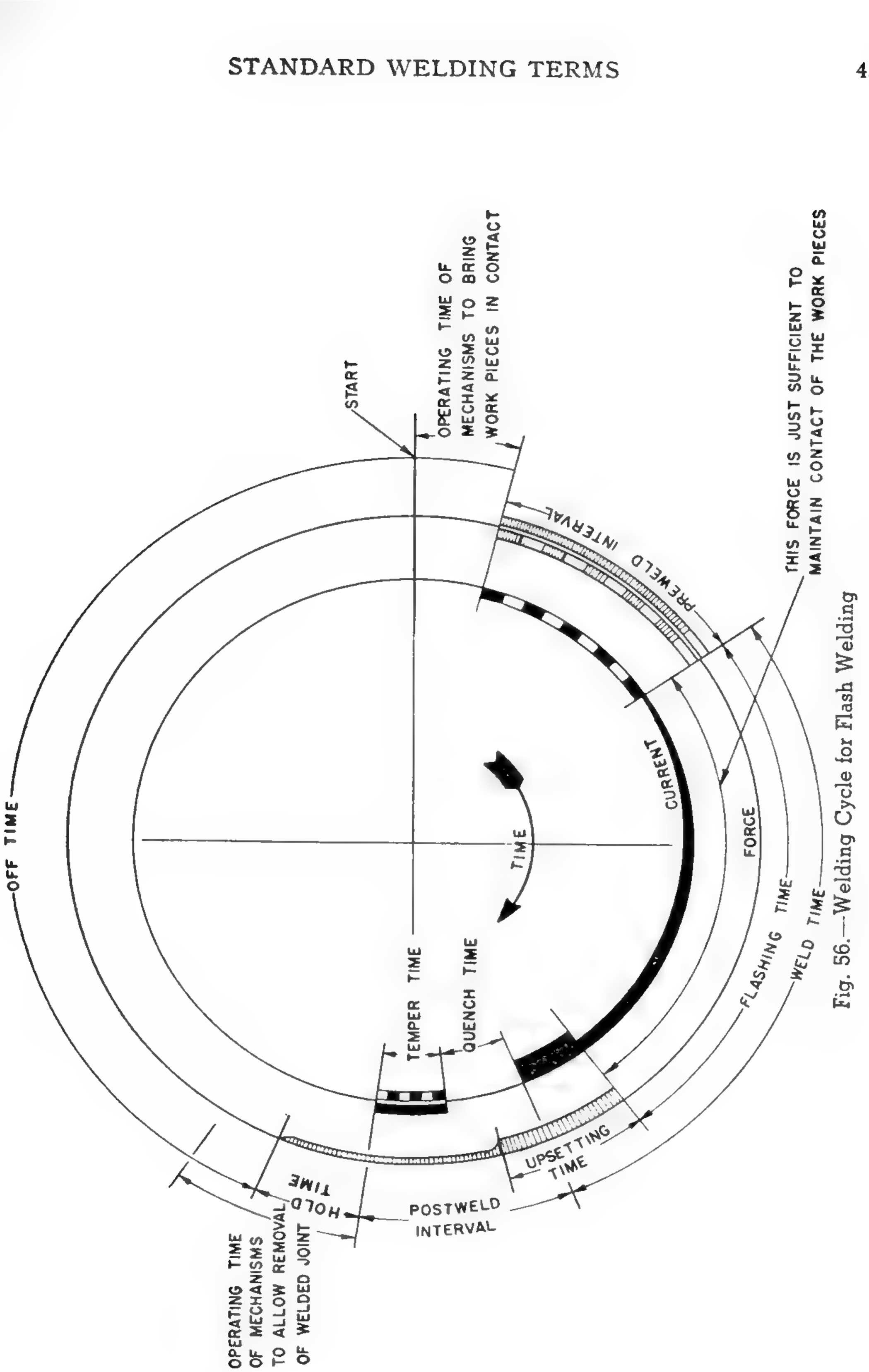


Fig. 56.—Welding Cycle for Flash Welding

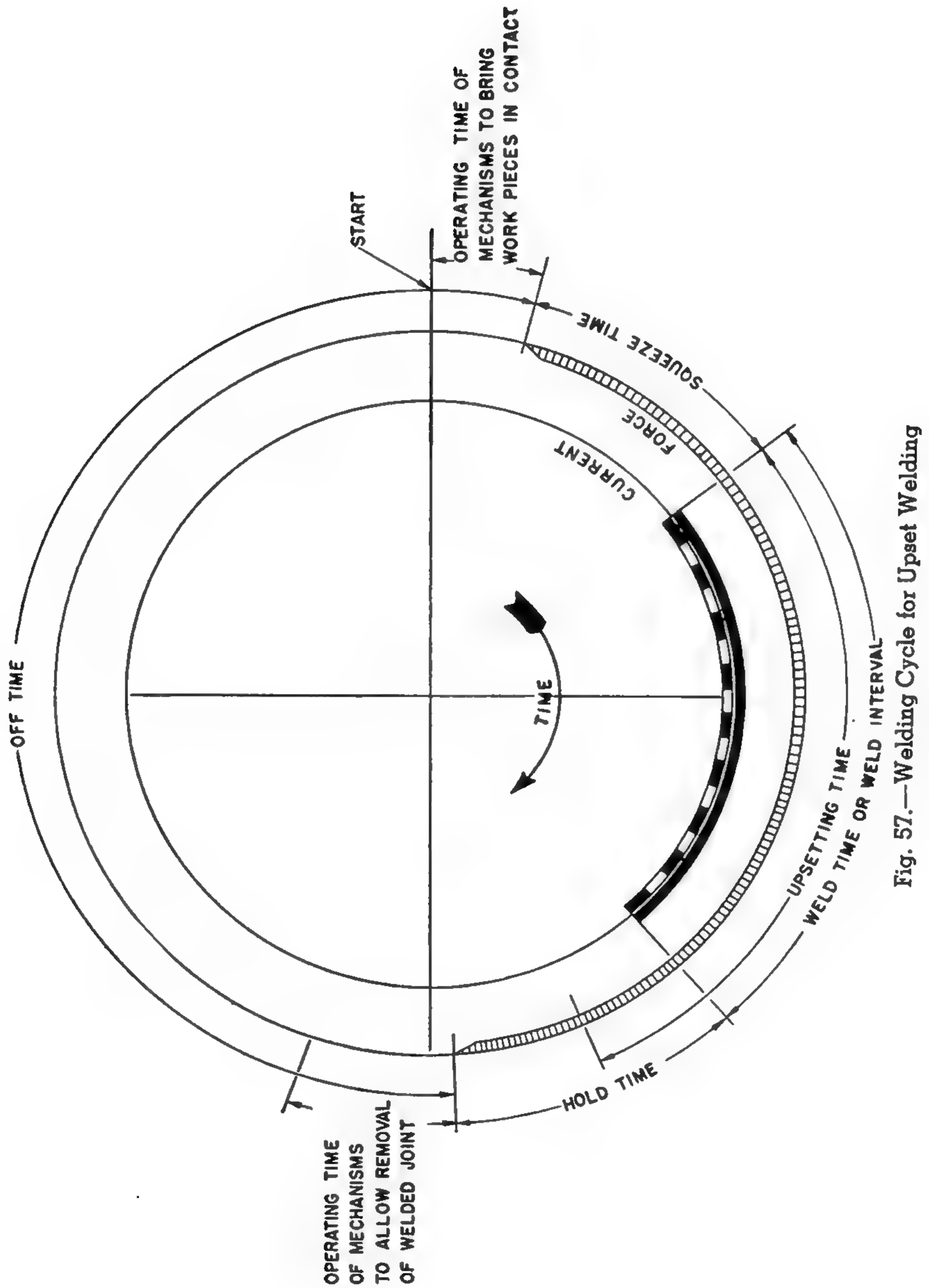


Fig. 57.—Welding Cycle for Upset Welding

CHAPTER 2

PHYSICS OF WELDING*

FOREWORD

WELDING INVOLVES more sciences and variables than any other industrial process, which may explain why most of those concerned are satisfied with a very crude understanding of its problems.

The principal sciences involved in welding are physics, chemistry and metallurgy. Of these, the physics problems are the ones most often neglected and least understood, particularly from the quantitative point of view. These involve heat, mechanics, elasticity, plasticity, electricity and magnetism, as well as those very complicated and as yet little understood phenomena of the welding arc. Testing and research work in this field require a knowledge of optics including polarized light, X-rays, X-ray diffraction, crystal theory and the constitution of matter.

This chapter is written for those who really wish to know the reason why and to acquire the habit of dealing with their problems quantitatively rather than qualitatively. It is not intended to imply that a welding engineer must or could be an expert in all of these branches of physics mentioned above. Moreover, it is obviously impossible to cover in this chapter, even superficially, all of these topics. However, it is hoped that the relatively simple applications discussed will help to stimulate a greater desire to understand the reason why as well as the habit of quantitative analysis. Even a modest degree of progress toward this goal would mean more for the advancement of welding, and for the sound and rational solution of its many complicated problems, than any quantity of empirical data not rationalized and explained.

There are two ways of attacking problems involving as many variables as do those in the welding field.

The Empirical Method.—This is the method most commonly employed and involves the making of many tests with many combinations of variables, in the effort to determine the effect of each by the process of elimination. Its chief difficulty lies in the fact that the number of experiments necessary for anything approaching dependable results is absolutely prohibitive. Moreover, if, as often happens, the experimenter is not fully aware of some of the significant variables which may vary from test to test without his knowledge, his results, when plotted against any given variable, yield what is commonly called a shotgun diagram rather than a smooth curve. In fact, this is the usual result in much of our so-called welding research, and is often due to the fact that the variables involved in the physics of the problem are not given due consideration, and that the quantitative analysis of these variables is not available to those concerned.

The Rational Method.—This involves first a careful review of the problem with respect to all of the known variables, and the elimination of those variables which are known to be of minor importance. This demands quantitative familiarity with the phenomena and the laws involved. The next step is a rational formulation of the relationships between the significant variables, in so far as such formulation is possible, and the solution of the resulting equations. This is much more possible with regard to the problems involving physics than to those involving metallurgy, and it is this opportunity which is usually overlooked. In fact, the whole purpose of this chapter is to point out the possibilities in this field and to stimulate intelligent interest therein.

As previously stated, it often happens

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* Prepared by a committee consisting of S. L. Hoyt, Battelle Memorial Inst., *Chairman;* E. Paul De Garmo, University of California; W. B. Kouwenhoven, Johns Hopkins University; C. F. Lucks, Battelle Memorial Inst.; R. C. McMaster, Battelle Memorial Inst.; F. C. Saacke, Air Reduction Sales Co.

that such rational formulation must involve crude approximations and that the resulting solution may not be quantitatively accurate. However, in many such cases it is possible to couple the rational attack with experimental research, by means of which the coefficients and sometimes the exponents in the simplified equations can be determined to cover the range of interest. Moreover, such research rationally planned on the basis of a thorough analytical study will be found to involve a small fraction of the total number of experiments necessary in the purely empirical method. Also the rational solution is vastly more valuable from the practical point of view than the empirical, since it not only yields an understanding of the reason why, but also gives a better picture of the relative importance of the several variables involved and the degree in which they affect the result. For example, the result may be proportional to some power of a given variable, fractional or otherwise, and the knowledge of this fact often indicates definite limitations in the practical application of the process in question, or it may indicate the most logical method of removing those limitations. Also, the rational solution may often be extended well beyond the range of the experimental research, although this should be done only with due recognition of the possible effect of some of the minor variables which were neglected in the original solution.

THE NATURE OF A WELD

Welding consists of the joining of two or more pieces of metal by the application of heat and sometimes of pressure. Welds accompanied by fusion are by far the most common, and these ordinarily do not require the application of pressure. When pressure is applied to a weld in which fusion takes place, the molten metal must be confined as within a solid mass of the metal. The weld may take place without fusion, if the parts are heated to such a temperature that cohesion of the adjoining faces takes place. This is usually accomplished by the application of pressure. Forge or other pressure welding is usually carried out at subfusion temperatures and mostly within the low, white heat range. Flash and upset welding are almost always done at subfusion temperatures, whereas spot welding usually involves fusion of a considerable part of the thickness of the two sheets involved. However, actual fusion at the boundary is not absolutely essential in a spot weld, although it is very difficult to apply sufficiently accurate control and timing of the heat delivery, to reach the welding temperature without passing over into the fusion range. Moreover, the surfaces would have to be free from all foreign substances as well as from any considerable oxide film.

In the case of welding dissimilar metals, welds may be made in which the metal with the lower melting point is melted and the metal with the higher melting point remains solid. In this case there is an alloy bond formed at the surface of the unfused metal. This type of weld may possess a great advantage in welding metals whose alloys form brittle compounds.

In the welding of dissimilar metals, a mistake has frequently been made of attempting to fuse the two metals together, whereas a surface alloy bond would in many cases be much more satisfactory. This type of bond is common in the brazing of such metals as copper, steel and cast iron. It has also been found possible in spot welding, by careful control, to melt one of the metals without fusing the other. In order to accomplish this it has been necessary to apply the heat in several steps, gradually approaching the melting point of the lower melting metal. In this way it is possible to avoid melting both metals.

APPROACH TO THE HEAT PROBLEM

A sound quantitative knowledge of thermal phenomena is absolutely essential to the solution of many important practical welding problems. Unfortunately, the theory of heat flow, particularly of transient heat flow, is not simple from the mathematical point of view. Moreover, both the thermal conductivity and specific heat, particularly at the high temperatures involved in welding, are difficult to obtain experimentally, and there is in consequence a considerable conflict between the data obtained by various experimenters.

Heat is a form of energy with exact equivalents in other forms of energy. Heat

flows from a region of higher temperature to a region of lower temperature according to the same laws as those of electricity in flowing from a region of higher potential to a region of lower potential. The steady-state heat flow between the two faces of a slab of any material is proportional to the difference in temperature between the two faces of the slab and inversely to the thermal resistance of the path, which in this simple case is proportional to the length of the path, to the thermal resistivity of the material and inversely to the cross-section of the path, exactly as in the case of an electrical resistance. The following differences should be noted:

1. In the case of an electrical conductor, the leakage from the surface of the conductor into the air or insulation which may surround it is in most cases quite negligible, whereas in the case of a thermal conductor, particularly at high temperatures, it is very difficult to insulate it sufficiently to avoid a considerable heat leak from the surface. In other words, the ratio of the electrical resistivity of electrical insulators to that of electrical conductors is many times greater than the corresponding ratio in thermal cases.

2. Except in the case of highly inductive electric circuits, that is, those with a large electromagnetic inertia, and of circuits with high distributed capacitance, the steady state of the current is established almost instantly after the electromotive force or potential difference between the two ends of the path has been established. In the thermal case the steady state may not be reached for minutes, hours or weeks. The reason for this is that when heat starts to flow in at the hot end of the path, a part and often a considerable part, is absorbed in raising the temperature of the zone into which it flows. It is only after the temperature of each zone has reached the steady state that this absorption of heat stops. Thus, if one end of a uniform bar 1 ft. long, having perfectly insulated sides (this is practically impossible), were suddenly raised to a temperature of 1000°F., it would be some time before any increase in temperature took place at the far end of the bar and a much longer time before the temperature of the far end approached closely to that of the hot end, even if the far end and the side walls were perfectly insulated. This would be analogous to an electric circuit which is made up of a lot of resistors connected in series, and shunted by capacitors, but not at all similar to a simple electrical conductor of uniform section. In fact, by a proper selection of constants, the capacitor-resistor combination can be made to behave electrically in exactly the same manner as the side-insulated bar behaves thermally, although the time necessary to reach the steady state may differ without affecting the equivalence.

The amount of heat absorbed by any thin slice or zone of the bar, due to a given increase in temperature, is proportional to what is commonly called the *specific heat* of the material. The higher the specific heat, the more will be the heat absorbed in transit and the longer will it take for the steady state to be reached, other things being equal. Also the higher the thermal resistivity the longer will be the transient period. The specific heat corresponds to the shunted capacitance per unit length in the analogous electrical circuit and the thermal resistivity to the resistance per unit length. There is nothing in the thermal problem which is analogous to the inductance or electromagnetic inertia of an electrical circuit.

The mathematics of this simple bar problem is by no means elementary and would be still less so if the normal practical boundary conditions were taken into account, under which heat is escaping from the side walls of the bar at a rate depending upon its temperature, the nature and thickness of the insulation and the ambient temperature. In fact, the insulation will itself pass through a transient state which is usually much longer than that of the bar.

In brief, the factor which is chiefly responsible for the complication of transient thermal problems is the heat-absorbing capacity of the materials involved. Thus, during the transient state there are two independent variables—time and space. That is, the temperature at any point varies with time, and the temperature at any time varies throughout the length of the path.

This problem will be treated more quantitatively in another part of this chapter.

In spite of these complications and mathematical difficulties, it is often possible by dividing the path into finite slices and with simple although laborious calculations to get an approximate no-

tion of the space and time distribution of temperature. Such calculations also help the investigator to acquire the habit of visualizing. They constitute the first step in quantitative thinking.

Heat Units and Thermal Properties of Materials

A *gram calorie* is the quantity of heat required to raise the temperature of one gram of water by 1°C.; more exactly the average throughout the range from 0 to 100°C., since the specific heat of water is not absolutely constant at all temperatures.

A *kilogram calorie* is equal to 1000 gram calories. When the word calorie is used alone, it may be assumed to refer to the gram calorie.

A *British thermal unit* (Btu.) is the heat required to raise the temperature of 1 lb. of water 1°F., or the average between 32 and 212°F.

Heat Equivalents.—One Btu. = 252 gram calories = 778 ft.-lb. = 1055 joules or watt seconds. One gram calorie = 4.184 joules.

Rate of flow is the number of quantity units per unit of time—calories per second, per minute or per hour; Btu.'s per second, per minute or per hour; or watts (joules per second).

One Btu. per second = 1055 watts.

One gram calorie per second = 4.184 watts.

The *thermal resistance* of any heat flow path is defined as the ratio of temperature difference between the ends of the path, to the rate of heat flow, i.e., to the number of heat units passing through the path in one unit of time. This is similar to electrical resistance which (for steady currents) is equal to the ratio of the difference of electrical potential between the ends of the path to the current flowing through it, i.e., the resistance in ohms is equal to the potential difference in volts divided by the current in amperes.

Unfortunately, in the thermal case there are two temperature scales (Fahrenheit and Centigrade, F. and C.),* two heat units (Btu. and calories) and three time units (seconds, minutes and hours). Although there is no universally employed unit of thermal resistance, the one most commonly employed in scientific literature is degrees Centigrade per calorie per second.

The *thermal resistivity* of any material may be defined as the thermal resistance between opposite faces of a unit cube of that material. This introduces another unit, that of length which may be 1 cm., 1 in. or 1 ft.; there are many possible combinations of basic units in which thermal resistivity may be expressed. Many heating engineers use as a working definition the difference in temperature in °F. necessary to drive 1 Btu. per hr. through a slab 1-in. thick and 1-ft. square of the material in question.

Thermal resistance may be most simply and conveniently expressed in terms of °C. per watt since the watt (one joule per sec.) is already a rate of flow. A heat path is said to have a resistance of 1 *thermal ohm* when, in the steady state, a difference in temperature of 1°C. is required to drive 1 watt of heat through it. Accordingly the thermal resistivity of a material is expressed in thermal ohms per centimeter cube. The use of this terminology is increasing rapidly and is particularly well suited to welding problems where the source of heat is so often electrical energy.

Thermal conductivity is the reciprocal of thermal resistivity. It is the watts per °C. per cm.³ or the thermal mhos per centimeter cube. Most of the data to be found in scientific literature give the thermal conductivity in calories per °C. per cm.³, but this can be converted to thermal mhos (watts per °C.) by multiplying by 4.184.

All calculations will be made by the use of thermal resistance rather than conductance. Moreover, since most welding engineers are more concerned with inches and °F. than with centimeters and °C., resistivities and other thermal properties will be presented in the more familiar units. The following symbols will be employed:

r_t = Thermal resistance in thermal ohms. °C. per watt.

r_t'' = Thermal resistance in thermal ohms. °F. per watt.

$$r_t'' = 1.8 r_t$$

ρ_t = Thermal resistivity in thermal ohm-cm. °C. per watt per cm.³

ρ_t'' = Thermal resistivity in thermal ohm-in. °F. per watt per in.³

$$\rho_t'' = 0.71 \rho_t$$

* Kelvin, °K. or °C. abs., is used sometimes.

Although resistance and resistivity, rather than conductance and conductivity will be used, conductivity values are also given in Table 1, for purposes of comparison with other data, which comparison will often disclose considerable differences, since accurate determinations are very difficult to make. In Table 1

γ_{tc} = Thermal conductivity in calories per sec. per °C. per cm.[3]
γ_{tw} = Thermal conductivity in watts per °F. per cm.[3]

$$\gamma_{tw} = 4.184\gamma_{tc}; \qquad \gamma_{tw} = \frac{1}{\rho_t}$$

Since ρ_t varies with temperature, values are given at two temperatures in Table 1. It usually increases with temperature, but decreases in aluminum and in 18–8 stainless steel.

As a general example, consider the simple case of parallel heat flow through a metal slab. Assume the space temperature gradient (the drop in temperature per inch length of path) to be T''°F., and compute the heat flow in watts per square inch of path section. It is, $p'' = T''/\rho_t''$ since both L and s are unity. Or for low-carbon steel $p'' = T''$ since $\rho_t'' = 1$ at low temperatures. For higher temperatures, ρ_t'' will increase and p'' decrease. If $T'' = 1000$°F. and $\rho_t''_{avg.} = 1.33$ (see Table 1), $p'' = 750$ watts per square inch. For stainless steel this would be 278 watts, for aluminum 3220 watts (more than ten times that for stainless steel) and for copper 5200 watts per square inch.

It should be noted that the gradient above assumed is 1°F. per mil (0.001 in.), whereas in spot welding thin sheets of stainless steel it may be several hundred °F. per mil in very short-time welds. That is, the rate of heat flow in such a case might easily be 50 kw. per sq. in. of spot area.

Table 1—Thermal Constants of Some Metals

Temperature, °F. →	γ_{tc} 200°	γ_{tc} 932°	γ_{tw} 200°	γ_{tw} 932°	ρ_t 200°	ρ_t 932°	ρ_t'' 200°	ρ_t'' 932°	K_e[a] × 10⁻⁶ 0–100°	K_e[a] × 10⁻⁶ 0–1000°
Pure iron	0.18	0.11	0.75	0.46	1.33	2.17	0.94	1.54	6.5	...
Low-carbon steel	0.17	0.10	0.71	0.42	1.41	2.38	1.0	1.66	7	8
High-carbon steel	0.12	0.07	0.50	0.29	2.0	3.42	1.42	2.42	6.3	8
Stainless steel, 18 chromium–8 nickel	0.045	0.05	0.19	0.21	5.3	4.8	3.78	3.4	11	...
Aluminum	0.49	0.63	2.05	2.64	0.187	0.38	0.346	0.27	12.3	16
Copper	0.9	0.86	3.76	3.6	0.265	0.277	0.188	0.196	9.3	...

[a] K_e is the coefficient of lin. expansion in in. per inch per °F.

Thermal Resistance of a Heat Path.—If the path has a constant cross-section of s square inches and a length of L inches and is composed of a material with a resistivity ρ_t'', its thermal resistance will be $r_t'' = \rho_t''(L/s)$ just as in the case of electrical resistance. If the cross-section is not constant, some equivalent value of L/s may be obtained by integration in those cases where that is possible, such as radial flow in a spherical or cylindrical shell, or by some means of approximation. This ratio L/s or its equivalent is sometimes referred to as the *geometric factor*.

If a temperature difference of T°F. be maintained between the ends of such a path, the heat flow (steady state) will be

$$p = \frac{T}{r_t''} \text{ watts}$$

or

$$H = \frac{p}{1055} = \frac{T}{1055 r_t''} \text{ Btu. per sec.}$$

Specific heat is defined as the ratio of the amount of heat necessary to raise the temperature of a given weight or mass of a material 1°, to that required to raise the temperature of the same mass of water 1°, at some specified temperature. It is therefore the number of heat units required to raise the temperature of a unit weight of the substance 1°, e.g., the calories to raise 1 gm. of the substance 1°C., or the Btu.'s to raise 1 lb. 1°F.

It is sometimes convenient to express this as joules per lb. (or per cu. in.) per °F. (or per °C.), but these are not true specific heats, although proportional thereto.

Average values of specific heat (h_s) are given in the fourth column of Table 2. These values apply for the range

from 70°F. to the temperature of fusion; they are average values, but are close enough for practical purposes.

Latent Heat of Fusion is defined as the additional heat required to transform a piece of metal of unit weight from the solid to the liquid state after it has already been raised to the fusion temperature, without further increase in temperature. Latent heat of fusion is usually expressed in Btu. per lb (H_t) as in column 6 of Table 2 or in calories per gram.

The values given for the three types of steel were not available; they have been assumed to be the same as for iron, which makes them somewhat high.

Table 2—Specific Heats, Latent Heats of Fusion and Total Heats of Fusion for Some Metals

Metal	T_f	$T_f - T_a$	h_s	$(T_f - T_a)h_s$	H_l	H_f	$J_{lb.}$	J''	g
Pure iron	2795	2725	0.16	436	115	551	581,000	163,500	0.282
Mild steel	2775	2705	0.155	420	115	535	564,000	159,000	0.282
High-carbon steel	2732	2662	0.15	400	115	515	543,000	153,000	0.282
Stainless steel (18–8)	2665	2595	0.14	363	115	478	504,000	142,000	0.282
Aluminum	1220	1150	0.27	310	170	480	506,000	49,400	0.098
Copper	1981	1911	0.11	210	88	298	314,000	101,000	0.323

T_f = fusion temperature of metal, °F.; T_a = room temperature; h_s = average specific heat for the range $(T_f - T_a)$; H_l = latent heat of fusion, Btu. per lb.; H_f = total heat of fusion, Btu. per lb.; $J_{lb.}$ = joules per lb.; J'' = joules per cu. in.; g = unit weight, lb. per cu. in.

Thermal Expansion

Since one of the most troublesome and most difficult problems connected with welding is that due to the expansion and contraction of the metal during heating and cooling, the coefficient of expansion or contraction is a vital thermal constant. This is given as K_e in Table 1 for the same metals thus far considered, and in inches per inch per °F. It varies with the temperature, but accurate values for all temperatures are not available.

Thus, if a bar of mild steel L inches long has its temperature raised by T°F., its increase in length will be K_eLT. If $L = 10$ in., $T = 1000$°F., and the average value of K_e throughout this temperature range is 8×10^{-6}, the expansion will be 0.08 inch.

If the bar is restrained from expansion, the resulting compressive stress will be K_eTE where E is the modulus of elasticity. Taking E at 30×10^6 the stress in this case would be 240,000 psi., provided that this were within the elastic range, which is not the case, since the compression yield point of this steel is only about 45,000 psi. In other words, the bar will be upset and permanently deformed by plastic flow.

If, on the other hand, this bar be allowed to cool through the same temperature range, but prevented from contracting by rigid restraint, it will be stressed far beyond the tension yield point, which is about 40,000 psi.

Thus the stress set up by heating or cooling under rigid restraint, is K_eE psi. per °F., which is, in the case of steel, about 240 psi. per °F., averaged over this high temperature range, or about 200 psi. per °F. in the low range. In the case of 18–8 stainless steel this will be 330 psi. per °F. in the low range and in the case of aluminum 123 psi. per °F. in the low range, E being only 10×10^6.

These are significant figures, since nearly every weld zone cools under partial restraint. In fact both design and welding sequence should be such as to reduce this restraint to the lowest point possible.

Surface Dissipation of Heat

When a surface is hotter than the surrounding air, heat is dissipated from it by both radiation and convection, which follow different laws. These phenomena are quite complicated and dependent upon the nature, shape and orientation of the surface, as well as upon the surroundings, particularly the velocity of the air in contact with the surface.

Although this general subject will be treated more in detail in a later section of this chapter, certain approximate relations will be noted for use at this point.

For moderate temperatures, 100 to 300°F., the total surface dissipation is

nearly proportional to the excess of the surface temperature over the ambient, or surrounding air temperature.

If θ_s is the surface temperature, θ_a the ambient temperature and v the velocity of the air in ft. per sec. with respect to the surface, then the surface dissipation H'' in watts per sq. in. is approximately

$$H'' = (\theta_s - \theta_a) \times 0.0044\sqrt{\frac{1.6 + v}{1.6}} = h\theta$$

where $\theta = (\theta_s - \theta_a)$ and h is the surface dissipation constant in watts per sq. in. per °F.

This is only a rough average and is influenced by many factors.

Thermal Time Constant

Consider a body of metal receiving heat at a constant rate, with a resulting increase in temperature and in surface dissipation. It will be assumed that at any instant the temperature of the body is the same throughout.

Let $(\theta_s - \theta_a) = \theta$, the excess of surface temperature over the ambient temperature.

Let C_b be the number of Btu.'s necessary to raise the temperature of the body by 1°F. This is sometimes called the *heat capacity* and is equal to the weight in pounds times the specific heat, or $C_b = wh_s$. It will be more convenient to express this in joules. C = joules per °F. $= 1055\ C_b = 1055\ wh_s$.

Let p = the constant rate at which heat is being delivered to the body, expressed in watts. Then the joules delivered in t seconds will be pt.

Start with the body at ambient temperature, i.e., $\theta = 0$ when $t = 0$. If there were no loss by surface dissipation the temperature would rise steadily at a rate equal to p/C °F. per sec. or $d\theta/dt = p/C$. In fact, it does *start* to rise at that rate, but as soon as the temperature rises above the ambient, surface dissipation begins. If S is the surface area in square inches and θ the temperature rise at any time t, the rate of dissipation is $Sh\theta$, or $D\theta$, where $D = Sh$ is the dissipation constant for the body in question. Thus, at each instant a part of the heat is being dissipated and the remainder goes toward raising the temperature of the body. Consider the instant t and the corresponding temperature θ.

$$p = D\theta + C\frac{d\theta}{dt} \qquad (1)$$

where p is the constant rate of heat delivery, $D\theta$ is the rate of surface dissipation and $C(d\theta/dt)$ the rate of heat storage, all in watts. At the start when $t = 0$ and $\theta = 0$, $d\theta/dt = p/C$ which is the slope of the temperature-time curve at the origin (see Fig. 1). As θ increases, $d\theta/dt$ must decrease since p is constant, and there will always come a time when $d\theta/dt$ approaches zero; that is, θ will approach a final limiting value equal to p/D.

Equation (1) is the same as that for the build-up of an electric current in an inductive circuit, or the charging of a condenser through a resistance. The solution of (1) is

$$\theta = \frac{p}{D}\left[1 - e^{(-Dt/C)}\right] \qquad (2)$$

where e is the base of Naperian logarithms (2.7183).

When $t = \infty$, $\theta = \frac{p}{D}$ as indicated above.

When $t = \frac{C}{D}$,

$$\theta = \frac{p}{D}\left(1 - \frac{1}{e}\right) = 0.632\frac{p}{D}.$$

C/D is called the time constant T of the system and is the time required for the temperature to reach 0.632 of its final value, p/D. This is a very important constant, whether dealing with the heating up of an electric motor under constant load and losses, of an underground cable or of a spot-weld zone. In the case of the motor, T is of the order 1 hr., for the cable many hours and for a spot weld in thin steel 0.01 sec. and much less for thin aluminum.

Application to Spot Welding

In order to illustrate the nature of this thermal time constant point of view, consider making a spot weld between two sheets of 0.02-in. aluminum.

Before considering the heat dissipation, it will be necessary to consider the rate of heat generation in the several parts of the weld zone due to the welding current. In any zone of electrical resistance r ohms, this is at any instant, $p = i^2r$ watts, where i is the current in amperes at the instant in question. But since the cur-

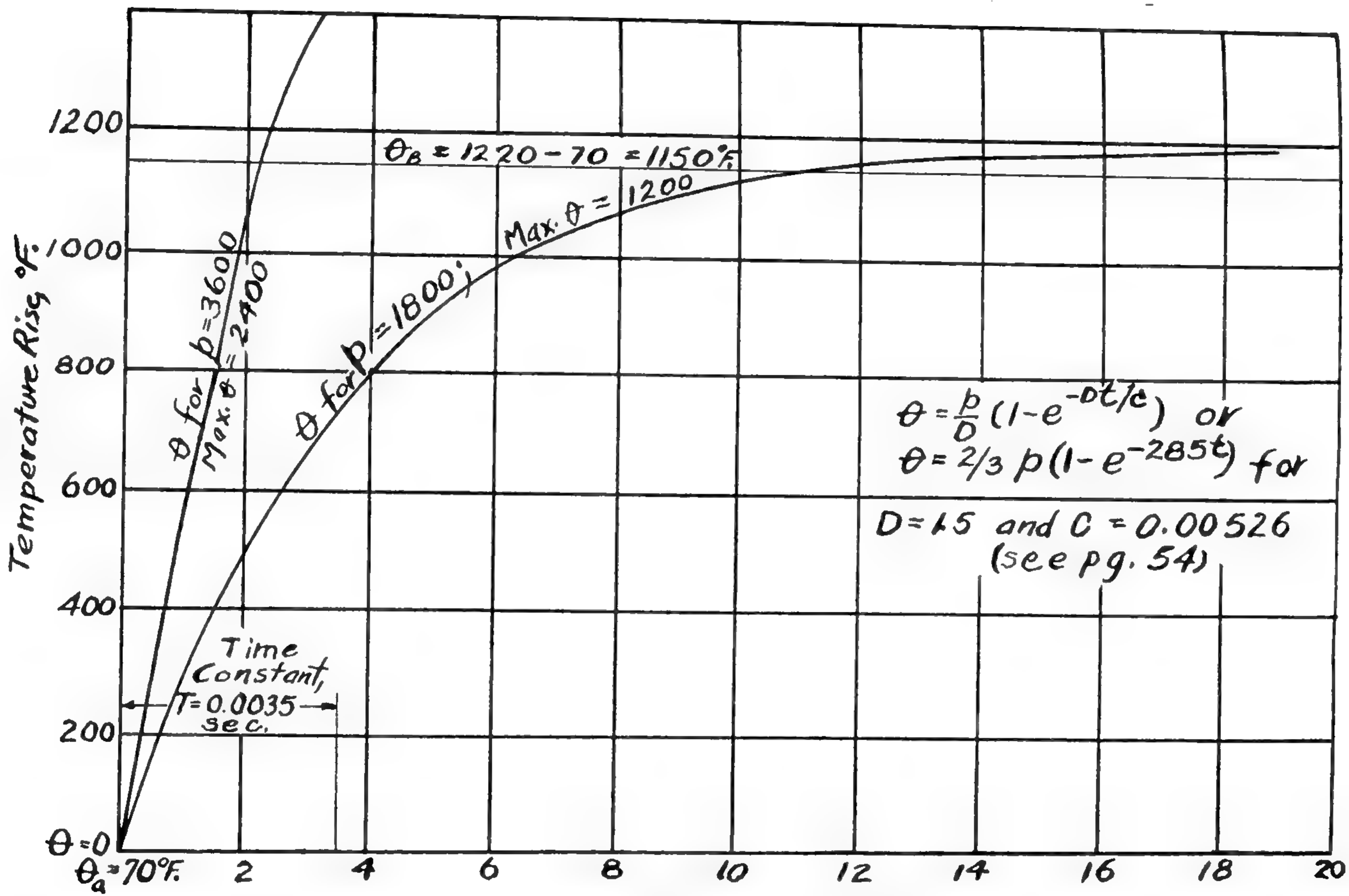

Fig. 1.—Temperature-Time Curves of Weld Zone for a Spot Weld Between Two Sheets of 0.02-In. Thick Aluminum

Watts between electrodes:	$p_1 = 3600$;	$p_2 = 7200$
Watts to body B: (See Fig. 2).	$p = 1800$;	$p = 3600$
Welding time, sec.:	0.02	0.003
Total joules between electrodes:	72	21.6
Joules to fuse body B:	6	6

Max. $\theta = 1200$ for $t = \infty$ and $p = 1800$

rent is not constant in spot-welding practice, and the rate of heat delivery varies widely according to the shape of the current wave, it will be necessary to assume an equivalent constant current and constant rate of heat generation, which is $p_{avg.} = I^2r$ watts, where I is the root-mean-square (rms.) value of the current during the welding period. Although this neglects any effect of current wave shape, it will be sufficient for the present purpose. Other refinements of analysis, such as taking account of the distribution of current in the weld zone, have no place in this thermal analysis, aimed only at a rough quantitative perspective.

The total electrical resistance between the electrodes may be divided into three parts: (1) r_i, the interface contact resistance; (2) r_m, the metal resistance of the sheets; (3) $2r_e$, the electrode contact resistance.

The relative magnitudes of these vary widely with different metals, different surface conditions, different pressures and different temperatures. Without a detailed discussion of these complicated relations, certain quantitative values will be assumed and an effort made to present a fair picture of the thermal phenomena.

For the purpose of this crude picture, assume that at the start, r_e is equal to the resistance of 10 mils thickness of the metal being welded and that r_i is equal to the resistance of 20 mils of the same metal. Both of these contact resistances drop rapidly with the increase of temperature and r_i will obviously disappear as soon as fusion starts at the interface.

As the temperature of the metal rises, its resistivity increases at the rate of about 0.25%* per °F. As the initial rate of heat generation is a maximum at the interface, the temperature and resistivity will rise most rapidly in that zone. Thus, the initial high r_i will be replaced in some degree by a thin layer of hot, high-resistivity metal which insures a maximum rate of heat generation in the interface zone.

In the meantime the relatively high initial rate of heat generation under the electrodes reduces the contact resistance r_e. Also the considerable heat developed at this point is carried off rapidly by the electrode material which is of high thermal conductivity. In fact, this is one of the fundamental requirements of the electrode material.

Thus, while the rate of heat generation under the electrodes is decreasing, that in the weld zone as a whole remains fairly constant or may even increase after a certain time. In any case, the weld zone has the highest temperature and heat flows therefrom in both directions to the much cooler electrodes. In fact, it is the magnitude of this heat flow and of the corresponding heat dissipation coefficient which are of primary interest in connection with this particular problem.

From the above crude picture it is obvious that anything approaching an exact analysis of the temperature distribution between electrodes throughout the welding period is impossible, not only because of the mathematical difficulties but also because of our lack of knowledge of both the electrical and thermal contact resistances of the interface and electrode contact zones. Any values assumed for these contact resistances are exceedingly crude and the quantitative results obtained therefrom should be accepted as indicating only the general relationships involved and the general nature of the phenomena. Even then they will be found to be very valuable from the practical point of view.

In order to reduce this particular problem to the basis of the thermal time constant concept, it will be assumed that the *body* consists of the central half of the region between the electrodes, labeled *B* in Fig. 2. This is substantially the weld zone, fusion zone or nugget of the conventional spot weld. Assume further, that heat is being delivered to this body at a constant rate and that as its temperature rises above that of the electrodes, heat will flow from the body

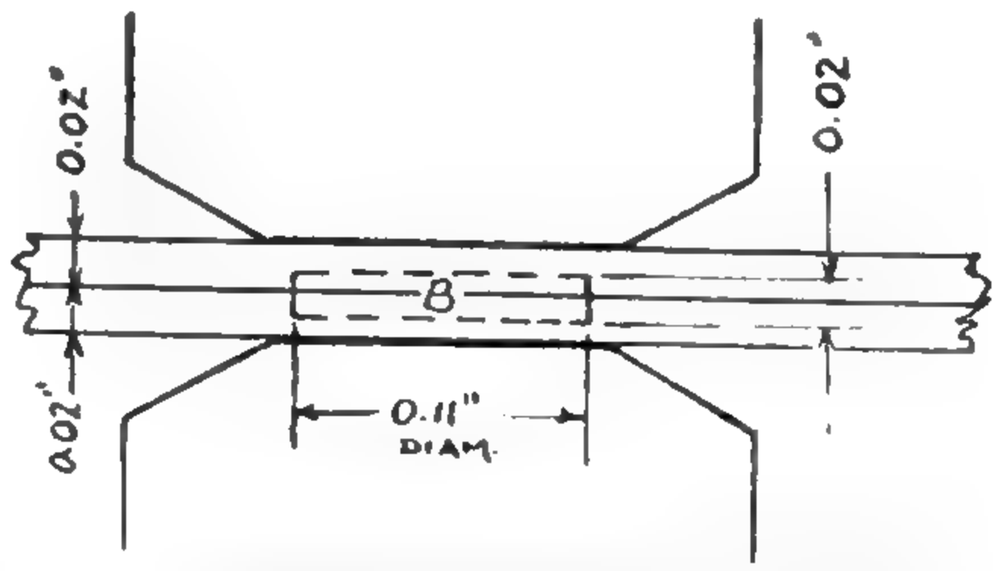

Fig. 2.—Aluminum Spot-Welded Specimen for Temperature Time Study

* This holds only for fairly pure metals. It is much less for high-resistivityalloys.

through the cylindrical discs between the body and the electrodes and through the thermal contact resistances between the electrodes and the sheets. Although this thermal contact resistance varies with both pressure and temperature, it will be assumed that at normal pressure and at the average temperature, the thermal contact resistance is equal to the thermal resistance of 10 mils (0.01 in.) of the metal being welded. This is probably too high, particularly at high temperatures.

The volume of the body B is one-half of the weld zone, and is, in this case, $V = 0.00019$ cu. in., and its weight, $W = 0.00019 \times 0.0976 = 0.0000185$ lb. Since the average specific heat of aluminum is 0.27, the heat capacity constant is

$$C = 1055\ Wh, = 0.00526 \text{ joules per } ^\circ\text{F.}$$

It cannot be assumed that the electrodes remain at ambient temperature throughout the welding period, since a considerable amount of the heat is generated at the electrode contact surfaces by the electrical contact resistance r_e. This can be roughly accounted for by reducing D to one-half of what it would be with constant ambient electrode temperature. This is equivalent to assuming that the electrode surface temperature rises half as rapidly as that of the body, which is a fair approximation for optimum welding conditions, although in some cases it may rise at a higher relative rate. However, one of the major requirements in spot welding is to keep this temperature below the danger point.

Thus the heat is dissipated from the body B, partly by conduction through the two thin discs between B and the electrodes, and partly by edgewise conduction into the surrounding sheets. The latter is usually much smaller than the former, and will be neglected in this very crude picture. Consider then, the conduction to the electrodes. The thermal resistance of the two paths in parallel is

$$r_t = \tfrac{1}{2}\left(\frac{p_t''\delta}{2S} + r_{te}\right)$$

where p_t'' is the average thermal resistivity of the metal, δ the thickness of the sheets, S the area of the spot or section of the heat flow path, and r_{te} the thermal resistance between each electrode and the work. But we have assumed above that

$$r_{te} = \frac{0.01 p_t''}{S}$$

Then,

$$r_t = \tfrac{1}{2} p_t'' \left(\frac{0.5\delta + 0.01}{S}\right) \text{ thermal ohm inches}$$

or, since $p_t''_{avg.} = 0.32$, $S = 0.0095$ sq. in. and $\delta = 0.02$ in., therefore, $r_t = 0.337^\circ$F. per watt. Since $D_1 =$ watts per °F., then $D_1 = 1/r_t = 2.97$ watts conducted to the electrodes per °F. difference in temperature between B and the electrode. But since it is assumed that the electrode temperature increases half as rapidly as the body B, the true D when expressed as watts per °F. of temperature rise of the body itself will be $D = D_1/2 = 1.48$, or, in order to simplify the numerical work, assume $D = 1.5$.

The resulting time constant will then be,

$$T = \frac{C}{D} = \frac{0.00526}{1.5} = 0.0035 \text{ sec.}$$

A little consideration will show that the separation of the whole weld zone into the body B and the two conducting discs is wholly artificial. Nevertheless B corresponds roughly to the familiar weld zone or nugget, and the maximum temperature gradient during much of the weld period is from B outward to the electrodes. However, this whole picture is based on conventional welding times, and would have to be altered to fit conditions that differ therefrom.

In spite of all the crude approximations the resulting picture is helpful in acquiring a quantitative perspective of this problem, particularly when analyzed with regard to different materials and different thicknesses.

Figure 1 shows the temperature-time curves for this particular case and for two different rates of power input, p. It should be noted that p is the power delivered to the imaginary body which is only one-half the weld zone, and that the power delivered between the two electrodes ($E_e I$), (where E_e is the rms. volts, between electrodes and I the rms. amperes) is about $2p$ in this case, more in some cases.

For thicker sheets, the thickness of the body B should remain the same (0.02 in.) for fast welds or increased slightly for slow welds.

It should also be noted that in making

an actual weld the power delivered is not constant in either the a.c. method or in the stored-energy method. Even thus both the time constant and the curves have real significance. In fact, this is just a starting point for a more thorough study of this whole problem, which is full of interest to the analytical mind, as well as of possibilities of practical value.

Although these curves and equations could be discussed at considerable length, only a few of the most significant relations will be noted.

1. If it were possible to measure the temperature at the interface and to plot it against time, the resulting curve would probably differ very materially from that shown in Fig. 1. In fact, at the start, and due to the high *initial* interface resistance, the temperature would rise more rapidly, and before the temperature of the remainder of the body had risen to any appreciable extent. However, the substantial equalization of temperature throughout the weld zone takes place very rapidly and the upper limit of that zone is determined by the ability of the electrodes to carry off the tremendous amount of heat conducted from the high-temperature weld zone through the intervening thermal resistance. In fact, it is altogether probable that in many cases of conventional welds, the electrode surface temperature rises considerably above that assumed, namely one-half the temperature rise of the weld zone. In this case the heat dissipation coefficient, D, would be reduced from the value computed above. If this process goes too far, the result will be overheated electrodes, surface burning, serious indentation and unnecessary waste of energy. In fact, this often happens when the rate of heat input is too low and the welding time correspondingly long. Also in this case, the upper part of the temperature-time curve would rise above that shown in Fig. 1 owing to the decrease of the dissipation coefficient D.

2. Unless the power delivered to the weld zone is sufficient to complete the weld in three or four times T sec., it will not be completed at all except when accompanied by the undesirable features mentioned in paragraph (1).

3. If p is sufficient but t is too long, the same undesirable results will ensue; e.g., if the curve corresponding to $p = 1800$ is considered, the only results of a welding time greater than 0.02 sec. would be a greater thickness of the fusion zone and perhaps some of the undesirable results mentioned above. The quantitative part of this statement may not be exact, but it is qualitatively sound.

4. The following relations are approximately true: T is proportional to the thermal resistivity of the metal, to its specific heat and to the square of the thickness, δ. Two sheets only are assumed.

5. A comparison of the two curves of Fig. 1 shows that when p is doubled, the total joules required to complete the weld is reduced to about one-third, owing to the fact that the heat loss increases even more rapidly than the welding time. In fact, in the case of the slow weld ($p = 1800$) the total joules delivered between electrode tips is about 12 times that necessary to fuse the weld zone, and even this is less than that under conventional welding technique. This heat loss decreases with increase of thermal resistivity and even more rapidly with increase of thickness.

This spot-welding problem has been discussed to some length, because it is an interesting example of the value of thermal arithmetic and provides a very useful aid to the visualization of the quantitative relations involved. It also indicates the value of more accurate quantitative experimental data which would make possible much closed approximations.

The analysis is wholly theoretical and makes no pretense at accuracy, although the general nature of the relations between the thermal properties of the material, the dimensions and the conclusions is correct.

Transient Heat Flow

Although the above discussion of the thermal time constant deals in a very crude way with both space and time-temperature changes, it does not attempt to deal with point-to-point variations of temperature throughout the region under study, as is necessary in many welding problems. For example, it is often of vital importance to know with reasonable accuracy the rate of cooling, in degrees per second, in several parts of the weld zone, since both the microstructure and the residual stresses are critically related thereto.

For each variety of steel there is a critical rate of cooling throughout the transformation range or at different parts of that range, above which the microstructure and the physical properties are

undesirable, and below which they are desirable, or at least acceptable. It is thus vitally important to be able to predict this rate of cooling for any given case, or to know how to modify the welding technique so as to keep the cooling rate within the desired limits. It depends upon the thermal properties of the material, upon the geometry of the setup and upon the rate and location of the heat delivery.

The rate of cooling of a spot weld may be obtained roughly by a reversal of the analysis given above, but it will vary with the welding time and the spread of the heat during that time.

From a purely theoretical standpoint this determination of cooling rate in most cases is a very difficult job. This is one of those cases where the rational attack must be supplemented by experimental research. It is also one of those cases where this method of attack not only saves a large amount of time in experimental work, but also develops a thorough understanding of the quantitative connection between the several variables and the result.

Methods of dealing quantitatively with such problems will be explained later on in this chapter.

THE GENERATION OF HEAT

Heat may be generated by electrical, chemical or mechanical means. Of the electrical methods for the generation of heat there are two of great importance—the electric arc and electrical resistance. A third method of electrical heating, by induction, is often considered separately but is really a resistance method in which the current is induced in, rather than conducted to, the piece in which the heating takes place.

The Electric Arc

The electric arc is a particularly suitable source of energy for welding since its heat is effectively concentrated. The energy input may be supplied from efficient electrical generators and transformers with suitable controls and response characteristics. Inert or special atmospheres may be used if desired. Large quantities of electrical energy are readily available at low cost in most industrial locations.

Although electric arcs have been used and studied for more than half a century their properties are complex functions of so many variables that only recently have there been established fundamental principles of general usefulness in predicting arc properties. These, for the most part, are limited in application to specific regions of the arc, and often to specific operating conditions. Much further study will be required before the design and control of practical electric welding arcs can be reduced to an exact, quantitative science.

The physics and properties of the arc column differ radically from those of regions of the discharge adjacent to the electrode and work surfaces. Welding arcs are subject to severe transients and rapid fluctuations in length, position, current and voltage, such that the average characteristics over any extended period of time may not correspond to any specific steady-state operating condition which can be evaluated quantitatively from available theory of the electric arc. The thermal time constant required for establishing equilibrium in any steady state is of the order of one millisecond. The welding arc is characterized therefore, by operation for short intervals in each of many steady states or equilibrium conditions, with rapid transients between these intervals.

The Arc Column.—The welding arc column is characterized by a nearly constant temperature of the order of 6000 ± 300°C. abs., throughout the length and diameter of the arc column. The ions, electrons, and neutral particles within the arc column are essentially in thermal equilibrium, that is, they have kinetic energies corresponding to the same temperature. The temperature of the surrounding gas a few hundredths of an inch from the boundary of the arc column is nearly that of the environment. The temperature of the electrode material probably cannot greatly exceed its boiling point. Consequently, tremendous temperature gradients exist in the well-defined boundary of the luminous arc column and at the ends of the arc column adjacent to the electrodes and the work.

The heat produced by the arc current flowing through the potential drop in the arc column is lost by conduction, convection and diffusion to the surrounding atmosphere and to the work or electrode. Most diatomic gases, such as oxygen and nitrogen, in the arc atmosphere are almost

completely dissociated at arc temperatures, and contribute greatly, like atomic hydrogen, to the transfer of heat. These dissociated atoms, together with the ions and electrons, recombine quickly in the surrounding cold gas or on adjacent surfaces of the work or electrode.

The temperature of the positive column is determined by the arc current, by the heat conduction and convection properties of the arc atmosphere and environment, and by the effective ionization potential of the arc gases. A change in any one of these factors produces corresponding changes in the voltage gradient and arc column diameter, such that the heat produced in the arc is equal to that transferred to the arc environment. Increasing the arc current tends to increase the column diameter, and, within limits, the arc column temperature. Increasing the heat-transfer ability of the arc atmosphere (as by increasing the gas pressure or by changing from argon to nitrogen or air, or by changing from air to hydrogen) reduces the arc column diameter and increases the temperature and the voltage gradient in the arc column. Lowering the effective ionization potential of the arc atmosphere, as by introducing easily ionized *arc-stabilizing* constituents in the electrode coating tends to lower the arc column voltage gradient and temperature. The electrical properties of the arc column are thus determined by the arc atmosphere and environment. Similar arc column temperatures and electrical characteristics may be obtained with different gases, provided the heat conductivities and effective ionization potentials of the arc atmospheres are similar.

Relatively small amounts of metallic vapors with low ionization potentials (5 to 8 volts) can greatly lower the effective ionization potential in the arc column from the values characteristic of atmospheric gases (14 to 16 volts). The number of ions, n_i, available to conduct the electric current through the positive column (as compared with the number of neutral gas molecules, N) may be estimated by Saha's equation:

$$\log_{10} \frac{n_i^2}{N} = -5040 \frac{V_i}{T} + \frac{3}{2} \log_{10} T + 15.38$$

This equation indicates that the ion concentration depends only upon the temperature, T (°C. abs.), and the effective ionization potential, V_i (volts). Since large quantities of metallic vapor with low ionization potentials are available in metal-arc welding, the temperature (as determined by the heat transfer characteristics of the gaseous atmosphere) is the major factor in determining the electrical characteristics of the arc column. Enclosing the arc within a thermal gas-producing shield, such as is provided by coatings of welding electrodes, has a significant stabilizing influence upon most welding arcs.

Within the arc column, the *voltage gradient*, E (volts/centimeter), is related to the total arc current, i (amperes), by

$$E = B/i^n$$

where B and n are constants. An increase in current is usually accompanied by a decrease in the arc column voltage gradient. This situation differs radically from the case of ohmic resistance, through which an increase of current requires an increase of applied voltage. This *negative resistance characteristic* of the arc column gives the volt-ampere curve of most arcs a negative slope. A series resistance, or ballast, is usually required to maintain arc stability from a constant potential source. Most welding generators, however, have drooping volt-ampere characteristics, so that stable operation is assured.

The Electrode Regions.—The arc column extends very close to the electrodes. In the case of an arc between tungsten electrodes in hydrogen, the total length of the electrode voltage drop region (outside of the arc column) has been measured as less than 0.001 mm. A considerable voltage drop, of the order of the ionization potential of the arc atmosphere, occurs within these electrode regions in the arc. Consequently, the electrode regions are characterized by tremendous local potential and temperature gradients. Considerable heat, with a magnitude approximately equal to the product of the electrode potential drop and the arc current, is produced in each electrode region and is probably transferred to the electrode or to the work material. Additional heat is supplied by recombination of dissociated molecules of diatomic gases and of ionized gases upon or near the surfaces. In many arcs, the voltage drop at the positive terminal is much higher than the voltage drop at the negative terminal.

In such cases, the greater heat produced at the positive terminal explains the general use of a polarity which makes the work positive and the electrode negative. This results from the fact that the work usually has the larger mass and, therefore, requires the greater heat input for proper fusion. This polarity is referred to as *straight polarity*. The energies corresponding to the terminal drops of voltage are most effectively utilized because they are delivered exactly where needed to melt the electrode at one terminal of the arc, and to melt the work at the other terminal of the arc, in preparation to receive the deposited molten metal.

Although the maximum heat is developed at the positive electrode in the case of several types of bare electrodes, the reverse condition is true in some cases with a covered electrode. With certain ionizing elements obtained with covered electrodes, satisfactory operation of the arc requires that the electrode be connected to the positive terminal of the welding generator. With this situation, greater heat appears to be developed at the work (negative terminal), as is evident from the increased penetration secured with this polarity, commonly called *reverse polarity*.

The supply of electrons and ions to conduct current in the electrode region is significantly influenced by the electrode properties and temperature. With short arcs, the phenomena at the electrodes of the arc consume a considerable part of the total voltage and may exert a significant influence upon the stability and ease of restriking of the arc. Refractory electrodes such as carbon and tungsten may attain high temperatures and have a copious thermionic emission. Low-boiling-point materials, on the other hand, may require higher applied voltages to restrike an arc and to continue adequate emission.

Welding Arc Characteristics.—The total voltage across the arc is composed of the electrode voltage drops, A, and the positive column voltage drop, Bl/i^n,

$$V_{arc} = A + Bl/i^n$$

where l is the effective length of the positive column. For a given welding current, the total arc voltage increases as the arc length is increased. With fixed generator settings, lengthening the arc tends to decrease the arc current. With fixed arc length, increasing the total applied arc voltage tends to increase the arc current. Typical welding arc characteristics (obtained with water-cooled iron electrodes to eliminate high voltage drop due to higher resistance in hot electrodes) are shown in Fig. 3. Short arcs, $^1/_{16}$ to $^1/_8$-in. long, with high currents (50 to 1000 amp.) are commonly used in arc welding. Under these conditions, the total arc voltages are usually relatively low (20 to 40 volts) in air, and somewhat higher in hydrogen.

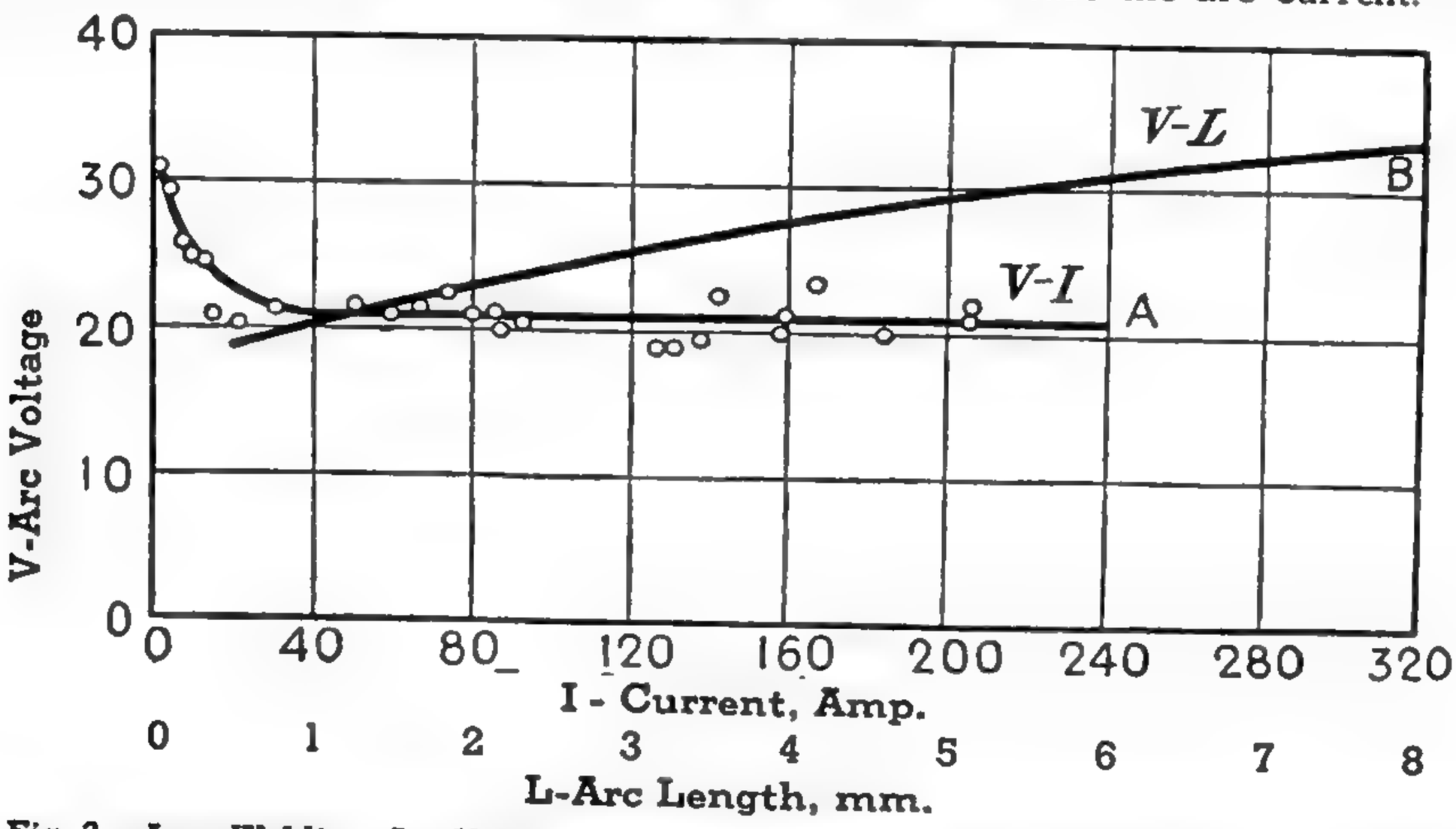

Fig. 3.—Iron Welding-Arc Voltage as a Function of Current (Arc Length = 1.17 Mm.) and of Arc Length (Current from 40 to 200 Amp.)

In order to start a welding arc with any

reasonable voltage, it is necessary to bring the electrodes in contact, and then make a gradual separation. This operation is referred to as *striking the arc*. A minimum open-circuit voltage satisfactory for striking a d.c. welding arc is about 60 volts, although a somewhat higher voltage, for example, 80 volts, would be preferable under many circumstances, if no penalty were attached to its use. In order to strike an a.c. arc, 60 to 100 volts is needed, depending upon the electrode used. Because of the necessity for frequent restarting, the a.c. arc is inherently less stable than the d.c. arc. If satisfactory operation is to be secured, factors favorable to arc stability, such as covered electrodes, heavy current, high-frequency ignition superimposed on the power frequency, and special constituents in the arc coating which tend to produce greater residual ionization, must be present.

from zero (during short-circuiting of the electrodes by the molten metal) to a maximum (after a large quantity of electrode material has been transferred). In some cases, two arcs exist in series while the metal drop is in transit, introducing two sets of electrode drop regions and consequently requiring unusually high arc voltages. These variations in arc voltage are common both with d.c. and with a.c. electrodes. In the latter case, additional voltage fluctuations are introduced by the extinction of the arc each time the electric current reverses.

Welding Arc Stability.—The stability of the welding arc, that is, its ability to reignite after short circuit or open circuit and after each reversal of alternating current, is determined by the reignition characteristics of the arc and by the recovery voltage characteristics of the supply circuit. Since the thermal time constant of the arc is short (of the order of a millisecond), deionization occurs quickly after the arc is extinguished. Voltages much larger than the steady-state burning voltage of the arc are required to produce reignition after arc extinction (Fig. 4). The dielectric strength of the electrode drop region builds up very rapidly (with non-thermionic electrodes) within 50 microseconds after arc extinction. The reignition voltage must be exceeded by the recovery voltage supplied by the external

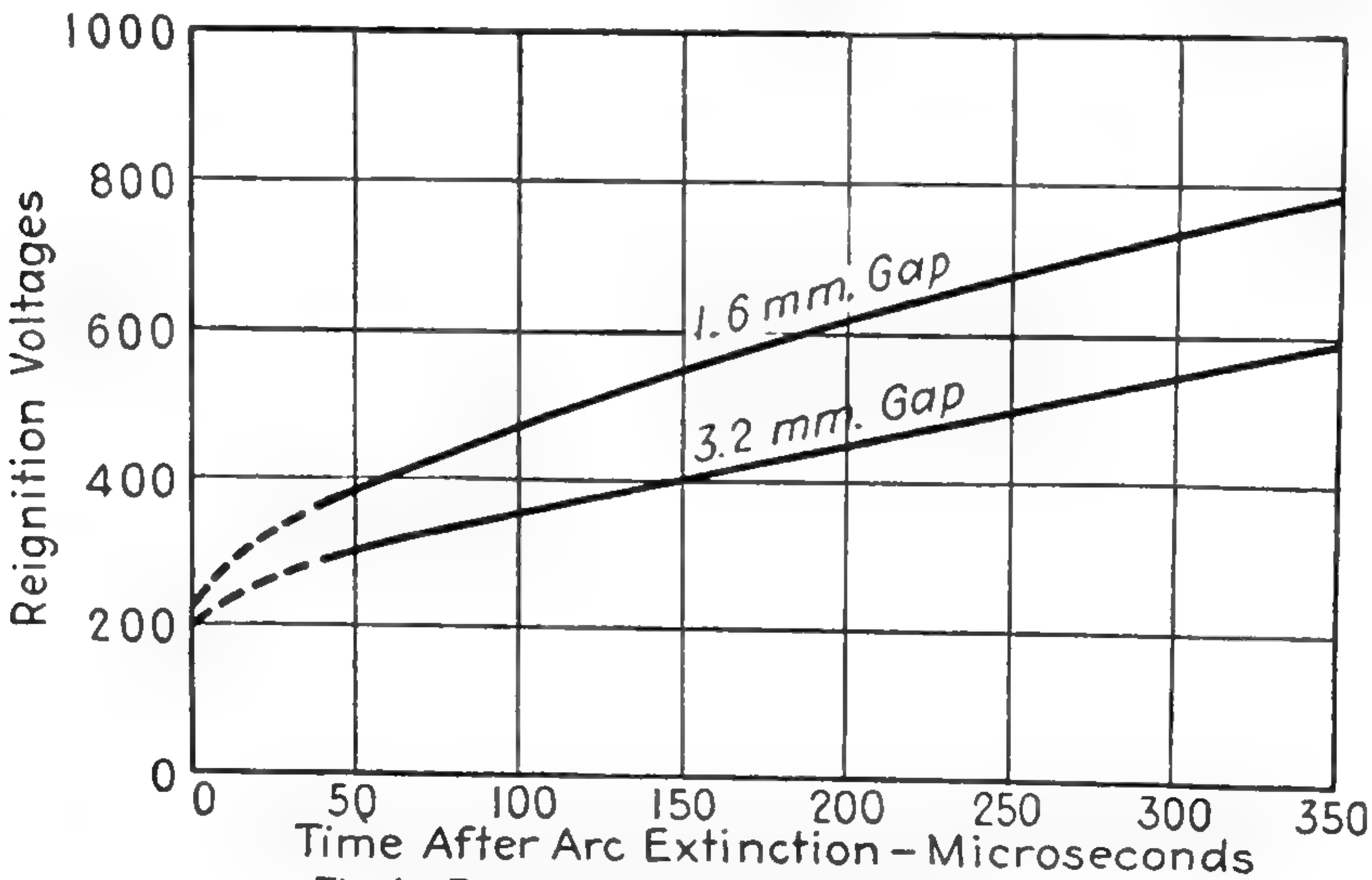

Fig. 4.—Recovery Strength of Short A.C. Arcs
(300 amp., 60-cycle, flat brass electrodes)

The high-current welding arc is subject to extremely rapid fluctuations of voltage and current caused by severe convection currents in the arc atmosphere, by transfer of metal globules, and by agitation of the molten metal electrode and work materials. All of these factors produce rapid variations in arc length. The transit of large metal drops across the arc introduces additional resistance (in the hot metal) and varies the arc length

circuit, if restriking of the arc is to occur. The low work function and low ionization potential of the coating material often provide considerable lowering of the reignition voltage and permit the use of supply circuits with lower open-circuit voltage characteristics. Thermionic electrodes such as carbon and tungsten have low reignition potentials because of their high operating temperatures and slow cooling after arc extinction. Superposition of high-frequency voltages, supplying perhaps up to 100 watts at 10^5 to 10^6 cycles, may increase the stability of a.c. welding arcs. This may be done by placing an auxiliary high-frequency transformer in series with the arc and by placing a by-pass condenser across the secondary of the welding transformer. The recovery voltage characteristics in the external circuit may be improved by means of higher open-circuit voltages, by means of severe inductances or by means of capacitances or other circuit elements designed to produce fast recovery voltage characteristics. Alternating-current welding arcs commonly require higher open-circuit voltages for stable operation than do d.c. arcs.

Rectification effects, such as are observed in the arc welding of aluminum in inert atmospheres with tungsten electrodes and a.c., are often caused by differences in recovery voltage characteristics between arcs with thermionic (tungsten) and non-thermionic (aluminum) cathodes. These may be controlled by proper balance between reignition voltage characteristics of the arc and recovery voltage characteristics of the external circuit, which may need to be biased for one-half of each cycle, as with series storage batteries.

Other Factors Influencing Welding Arcs.—The magnetic field of the welding current, particularly important during welding of ferromagnetic materials, may react with the current to produce a force upon the arc column, or *arc blow,* tending to move and lengthen the arc. This effect is essentially absent with a.c. arcs, and is most pronounced with d.c. arcs near the end of a plate where the current flows to the arc from only one side.

The rate of electrode burn-off in the welding arc appears in many cases to be almost linearly proportional to the arc current, and is not greatly influenced by the arc voltage. Polarity has a large influence; with certain metals and atmospheres, the electrode burn-off rate with straight polarity (electrode negative) may be twice as large as the burn-off rate with reverse polarity. The type of electrode and coating also have a significant influence. Burn-off characteristics influence the arc length and metal transfer, and are influential in determining arc stability and characteristics.

Metal transfer phenomena in the welding arc are difficult to measure or evaluate. Metal transfer from some electrodes, such as the common E6010 electrode, occurs in large molten drops or globules. In flat position welding, these molten drops pour out of the electrode into the molten pool in the work, often shorting the entire arc gap. The short-circuit current flowing through the metal globules heats them rapidly by ohmic losses, and the last conducting filament usually explodes violently and restrikes the arc. Magnetic forces apparently contribute to the expulsion of electrode material, and overhead welding is entirely feasible. On the other hand, electrodes such as the E6020 type provide spray-type metal transfer, with no shorting of the arc by large drops. A detailed study of the physics of metal transfer is beyond the scope of this chapter. However, it is evident that metal transfer characteristics have a large influence upon welding arc characteristics.

In addition to providing protective atmospheres, thermal shielding and stabilizing constituents to the welding arc, electrode coverings often supply fluxes and slag-producing constituents. The latter greatly influence the quality of the weld metal by providing thermal insulation, by preventing undesirable oxidation, by maintaining fluidity until inclusions and gases may escape to the surface of the bead, or by supplying alloying constituents to the weld metal. Large quantities of gases, such as hydrogen, may be dissolved in the molten steel. With some alloys dissolved hydrogen may contribute to underbead cracking unless the weld is made in an atmosphere which has only a small quantity of this gas present, and weld cooling occurs under properly controlled conditions. Consequently it may be necessary to use arc atmospheres modified from those providing maximum arc stability or ideal heat-transfer properties.

Electrical Resistance

The electrical resistance method for the generation of heat has been discussed previously in this chapter in the example illustrating the application of the concept of thermal time constant to spot welding. As mentioned there, the resistances are body resistances and resistances at the various contacting surfaces. Body resistance is proportional to the resistivity of the material and the length of the current path, and inversely proportional to the area of the current path. Contact resistance is very much affected by surface conditions; that is, by cleanliness and freedom from oxides or other chemical compounds, and by the roughness or smoothness of the surface. It also is a direct function of the resistivities of the materials in contact, and inversely proportional to the pressure. With given materials, of uniform surface condition, pressure becomes the major factor in the determination of contact resistance. The natural oxides, such as mill scale on steel, are of such non-uniform quality as to render uncertain the control of energy in resistance welding. It is therefore preferable to remove these oxides by pickling or to prevent their formation by cold rolling and controlled atmosphere annealing. It is evident that for materials of high resistivity, and for the heavier gages of material, the body resistance is of major importance and the contact resistance of relatively less importance. For high-conductivity materials, on the other hand, contact resistance is of the utmost importance. This results in the use of as light pressures as possible, which tends to permit cracking of welds in thin sheet, and porosity in welds made in heavier gage material. Differences in resistivity are reflected in rather widely different currents required to make the same size weld in various materials. In general the magnitudes of the resistances involved are small, of the order of less than 0.0001 ohm.. Hence the currents are large, running into the thousands and tens of thousands of amperes. It is most convenient to supply such currents from alternating current systems, making use of transformers for stepping up the current.

It appears in the case of steel that contact resistance largely disappears during the first half-cycle of the flow of current. It might seem, therefore, that contact resistance would be of little importance. However, the greatly increased generation of heat during the first cycle, made possible by contact resistance, causes a significant increase in body resistance which rises with temperature. This boost in body resistance makes the remainder of the current more effective. The importance of contact resistance in materials of medium resistivity, such as steel, is borne out by the fact that higher pressures, which reduce contact resistance, necessitate higher welding currents.

Combustion of Gases

Of all the gases which are available for combustion with oxygen, the burning of acetylene in oxygen results in the highest flame temperature. Another combination which results in a high temperature is the burning of hydrogen in oxygen. This flame has long been used for the welding of low melting point metals, such as aluminum. The temperature of the oxy-acetylene flame is generally credited with being about 3200°C., which is ample for the welding of steel. The burning of acetylene in oxygen at the orifice of a torch takes place in two steps. The first of these is the burning of carbon to carbon monoxide, the hydrogen remaining unconsumed. This takes place in a small bluish-white cone close to the torch in which the gases are mixed. It is this part of the reaction which gives rise to the heat which is most effective for welding. The burning of the carbon monoxide to carbon dioxide and of the hydrogen to water vapor takes place in a large blue flame which surrounds the welding operation but contributes only a preheating effect to the welding operation. The equations representing these two steps of combustion are as follows:

$$C_2H_2 + O_2 \longrightarrow 2CO + H_2$$

$$2CO + H_2 + 1^1/_2O_2 \longrightarrow CO_2 + H_2O$$

The first reaction above generates heat by the breaking up of acetylene as well as by the formation of carbon monoxide. The dissociation of each gram molecular weight of acetylene liberates 54.3 kg. cal. at 15°C. (254 Btu. per cu. ft. of acetylene at 68°F. and 14.7 psi.). The combustion of the carbon to form two moles of carbon monoxide liberates 52.9 kg. cal.[11] (247

Btu. per cu. ft. of acetylene). The total heat supplied by the first reaction is therefore 107.2 kg. $cal._{15}$ (501 Btu. per cu. ft.).

The second reaction liberates 68.4 kg. $cal._{15}$ (320 Btu. per c. ft.) by the burning of the hydrogen to water vapor. The combustion of each of the two moles of carbon monoxide provides 68.0 kg. $cal._{15}$ (318 Btu. per cu. ft.), or an additional 136.0 kg. $cal._{15}$ (636 Btu. per cu. ft.) for the reaction. The total heat supplied by the second reaction is therefore 204.4 kg. $cal._{15}$ (956 Btu. per cu. ft.).

Adding the heat supplied by the two reactions gives the total heat of combustion for each mole of acetylene, which is 311.6 kg. cal. The above energy is equivalent to 1456 Btu. per cubic foot. The concentrated heat liberated by the first reaction in the small inner cone of the flame is 34.4% of the total heat, or 501 Btu. per cubic foot. The remainder of the heat is developed in the large brush-like outer envelope of the flame, and is effective for preheating. It is this heat which makes the great difference in cooling rate between oxy-acetylene and electric arc welding, which is one of the most characteristic differences between these processes. It is seen from the above reaction equations that one volume of oxygen is used in the first step of the combustion to burn one volume of acetylene. This oxygen must be supplied in the pure state. The one and one-half volumes of oxygen required in the second step are picked up from the atmosphere. When just sufficient oxygen is supplied to burn the carbon to carbon monoxide, as indicated in the first step above, the resulting flame is said to be neutral. If less than enough oxygen is supplied to complete the combustion of the carbon, the flame is said to be reducing or an excess acetylene flame. This flame has certain uses in welding, and is discussed in Chapter 5. With more than enough oxygen for the first reaction above, the flame is oxidizing, which is detrimental for most welding.

The burning of hydrogen is a simple reaction with oxygen to form water vapor. The total heat of this reaction was given above as 68.4 kg. $cal._{15}$ per mole. This corresponds to 320 Btu. per cubic foot. If sufficient pure oxygen were supplied to completely burn all of the hydrogen, the flame temperature would be approximately 2900°C. However, this would not provide a protective outer envelope of reducing atmosphere, and consequently would be impractical. If only enough pure oxygen to burn half of the hydrogen is provided, the concentrated heat would be 34.2 kg. cal. per mole, or 160 Btu. per cubic foot. In this latter case the flame temperature would drop to a little over 2500°C. Comparing this temperature with 3200°C. for the acetylene flame, it is seen that with an oxy-hydrogen flame the temperature difference above the melting point of steel is only about 1000°C. in contrast to about 1700°C. for the oxy-acetylene flame. The oxy-hydrogen process is obviously much slower for the welding of steel. It may be noted that by adjusting the amount of oxygen supplied, the relative proportions of concentrated heat and outer flame preheat may be varied. A similar control of the acetylene flame is not available, since any attempt to reduce the relative amount of the outer envelope heat results in an oxidizing flame, and a change in the other direction results in a carburizing flame.

Replacement of Metal in Compound—Thermit Welding

The molecular heat of formation of alumina is 399.0 kg. cal., a value greatly in excess of that of any other element. The heat of formation of iron oxide, Fe_3O_4, is 265.2 kg. cal. When metallic aluminum in the form of powder is mixed with powdered iron oxide, the reaction may be started by the burning of magnesium powder. The iron oxide is reduced at the expense of the aluminum, and the heat generated is sufficient to raise the temperature of the whole to about 3000°C., or about twice the melting point of steel. The reaction is

$$8Al + 3Fe_3O_4 \longrightarrow 9Fe + 4Al_2O_3 + 800.4 \text{ kg. cal.}$$

The excess heat in the steel forms a convenient method of welding heavy sections of iron or steel, and this is known as the thermit welding process. The fundamental advantage of this process is that the single contraction and slow cooling of the entire mass of weld metal in heavy sections result in a minimum of residual stress. When the section to be welded is restrained from contracting by the remainder of the structure, the single contraction may be compensated for by

prior elastic deformation or thermal expansion of other portions of the structure, applied in such a way as to open the joint before welding.

Recombination of Molecules—Atomic Hydrogen Welding

The recombination of single atoms to form diatomic gas molecules results in the liberation of heat which is of importance in welding. Atomic hydrogen liberates 50.4 kg. cal. per mole (236 Btu. per cu. ft.) in recombining to the stable molecular state. An additional 68.4 kg. cal. per mole (320 Btu. per cu. ft.) is generated by burning in the air surrounding the weld of the molecular hydrogen to water vapor. This combustion effectively shields the molten weld metal from oxidation and the formation of nitrides. It also provides some preheat to the plate, and helps to retard cooling.

The dissociation of the gas may be brought about by passing it through an electric arc. When a plate of steel is placed in the path of the atomic hydrogen issuing from the arc, it serves to chill the gas sufficiently to favor immediate recombination at the surface. The heat is therefore delivered exactly where it is needed and the gas serves effectively to transfer energy from the arc to the surface.

Mechanical Methods

Mechanical methods for the generation of heat, like many chemical methods, have not found practical application in welding processes. This has been either because the generation of heat was insufficient in magnitude or in concentration. Friction and impact may under certain rare circumstances produce sufficient heat to make a weld. A steel tube may be revolved at high speed against a friction plate, until its temperature is above the critical and the metal is in a plastic condition. In this condition the end of the tube may be spun around and closed. However, the quality of the closure is under suspicion because of the possibility that oxide has been trapped in the joint.

The principal points with regard to any methods used for the development of welding heat are the intensity or concentration of the heat and the ability of the preparation or process to provide properly cleaned surfaces.

DISSIPATION OF HEAT

The dissipation of heat from the place at which it is generated is one of the factors controlling temperatures during the formation of a weld. Furthermore, after the generation of heat ceases, the manner in which cooling takes place has a profound influence on the properties of the weld and the adjacent metal. Heat tends to go to a region of lower temperature and of itself will only go along paths of decreasing temperature. The modes of heat transfer are commonly classified as conduction, convection and radiation.

Conduction

Problems involving the conduction of heat are divided into two general classes, constant and variable heat flow. In the former the heat flow is constant and the temperatures throughout the material are independent of time. In variable heat flow, the heat flow and the temperatures in the material change with time. Practically all welding conduction problems are of the variable heat flow type. Mathematical expressions for the two classes of heat flow by conduction are given by Glazebrook, Schack, Bruce and McAdams.

Properties of Material Governing Heat Flow.—The Fourier equations for heat flow in one direction are sufficient for a consideration of the properties of a material which govern the flow of heat. The equations are, for constant heat flow

$$q = -KA\frac{dT}{dx} \qquad (3)$$

and for variable heat flow

$$\frac{\delta T}{\delta t} = \frac{K}{C\rho}\frac{\delta^2 T}{\delta x^2} \qquad (4)$$

The significance of these symbols is shown in Table 3.

In the steady state or constant heat flow the only property of a material governing heat flow is thermal conductivity (equation *3*). In variable heat flow, the instantaneous heat flow for a given point and temperature gradient is also governed solely by thermal conductivity. However, the temperature gradient changes with respect to both time and position, and hence other factors enter. The change in temperature with time is given by equa-

Table 3—Legend of Equation Symbols

Symbol	Description	Commonly Used Units
q	Quantity of heat flowing through the area A per unit time	Watts, cal./sec., Btu./hr.
A	Cross-sectional area through which the heat flows	Cm.², ft.²
x	Distance in direction of heat flow	Cm., in.
T	Temperature	°F., °C.
t	Time	Sec., hr.
K	Thermal conductivity	Watts per cm.² per °C. per cm.; cal. per sec. per cm.² per °C. per cm.; Btu. per hr. per ft.² per °F. per in.
C	Specific heat	Cal./gm.; Btu./lb.
ρ	Density, the mass per unit volume	Gm./cm.³; lb./ft.³

tion *4*. Examination of this equation shows that a high thermal conductivity and low specific heat and density make for rapid heat flow. The term $K/C\rho$ is called the *thermal diffusivity* of a material.

Temperature Factors Governing Flow of Heat.—A temperature difference between positions in any material is a prerequisite for heat flow, the amount of flow being related directly to it. The values of the properties of a material governing heat flow are dependent upon temperature.

The thermal conductivities of iron and low-alloy steels decrease with increase in temperature. The thermal conductivity of a high-alloy steel increases with increase in temperature. Thermal treatment may also affect thermal conductivity. Alloys of the same composition heat treated differently will have, in general, different thermal conductivities.

The specific heat of alpha iron increases with temperature up to the magnetic transformation. Between this and the gamma iron transformation a decrease with increase in temperature takes place. Above the gamma iron transformation the specific heat again increases with temperature, the increase being much less than that for alpha iron except at the transformation point. The density of iron decreases with increase in temperature.

Several studies have been made of the effects of cooling rates of welds. Reports of these studies are listed in the bibliography at the end of this chapter. In a study of the effects of the cooling rate on the properties of arc-welded joints in carbon-molybdenum steel plates, the cooling curves for actual welds were superimposed on the S-curves for the particular steel to obtain an indication of the suitability of the welding conditions with respect to the effect on the metal in the heat-affected zone. The type of structure and the approximated hardness to be expected can also be obtained by this method.

Heat Flow Problems.—Rectangular parallellopipeds and cylinders are the shapes most frequently met with in problems involving constant heat flow. The equations for the two shapes are:

Rectangular parallellopiped

$$q = KA\frac{\Delta T}{\Delta X} \qquad (5)$$

Cylinder or cylindrical shell

$$q = 2.73\frac{KL\Delta T}{\log_{10}(b/a)} \qquad (6)$$

where

q = Heat flow per unit time (radially)
ΔX = Thickness
ΔT = Temperature difference
L = Length of cylinder, in the same system of units as K is expressed
a = Inner diameter
b = Outer diameter

The solution of problems involving variable heat flow are more difficult than for constant heat flow. The general equation for variable heat flow in three dimensions is

$$\frac{\delta T}{\delta t} = \frac{K}{C\rho}\left(\frac{\delta^2 T}{\delta x^2} + \frac{\delta^2 T}{\delta y^2} + \frac{\delta^2 T}{\delta z^2}\right) \qquad (7)$$

where x, y and z = distances along axes of a rectangular coordinate system.

The heating or cooling of a body by exterior means involves an additional term for the transfer of heat between its surroundings and the surface of the body. Gurney-Lurie charts are available by which solutions for this type of problem

may be obtained. With such factors as thermal conductivity, specific heat, density and surface heat transfer coefficient known, the time of heating, the time required for a given point in the body to reach a given temperature and other quantities may be calculated for slabs, cylinders, spheres and semi-infinite solids.

Table 4—The Thermal Conductivity, Specific Heat and Density of Iron at Various Temperatures

Temperature, °C.	Thermal Conductivity, Cal./Cm.²/Cm./Sec./°C.	Specific Heat, Cal./Gm	Density, Gm./Cm.³
	Alpha Iron		
0	0.173[a]	0.104	7.87
200	0.145	0.128	7.82
400	0.117	0.151	7.74
600	0.091[a]	0.188	7.67
800	...	0.210	...
	Gamma Iron		
1000	...	0.162	...
1200	...	0.165	...
1400	...	0.169	7.42

[a] Extrapolated.

In welding, the temperature at a given point and the time or the rate of temperature change with time are of greatest interest and in the reports of many investigation equations will be found for calculating the temperature of a weld for various welding conditions. These equations permit the calculation of the temperature at any point at any time after the arc is broken. An equation has also been established for determining the temperature at a point in the neighborhood of a single bead deposit on the surface of a very large, thick plate. This equation has been further developed for the case of an intermediate plate which is too thick to be welded by a single bead but too thin to be considered as an infinite plate.

An electrical analogy method of establishing cooling curves of welds has been developed whereby the actual heat-flow problem is simulated electrically. Calculations may be made to convert the measured electric units into the desired heat units.

Thermal Conductivity, Specific Heat and Density Variations with Temperature. —Table 4 gives the thermal conductivity, specific heat and density of iron. Table 5 gives the thermal conductivities of some of the commonly used metals encountered in welding.

Convection

Circumstances Favorable to Convection. —Convection is the term applied when heat is transferred by the movement, as a whole, of the substances being heated or cooled and may be natural, as rising air adjacent to a heated wall, or forced, as mechanically blowing air over the wall. It is practically impossible to separate heat flow by conduction and convection when heat flows from a surface to an adjacent medium. Langmuir developed the film theory for heat transfer of this type. He assumed that near the surface laminar flow would be present and that the temperature gradient through this region would be almost linear. Beyond this region the flow would be turbulent and the temperature would be that of the main part of the medium. Kennard conducted experiments which showed that

Table 5—Thermal Conductivities of Some Commonly Used Metals

Material	Thermal Conductivity, Cal./Cm.²/Cm./Sec./°C. 100°C.	200°C.	300°C.	400°C.	500°C.
Basic open-hearth iron	0.159	0.145	0.131	0.117	0.104
Low-carbon steel	0.193	0.165	0.140	0.123	0.109
Medium-carbon steel	0.180	0.154	0.125	0.105	0.091
High-carbon steel	0.162	0.132	0.109	0.085	0.075
18–8 stainless steel	0.037	0 041	0.045	0.048	0.052
Chromium steel	0.060	0.062	0.064	0.066	...
High-chromium steel	0.050	0.052	0.055	0.057	0.058
Copper	0.923[a]	...	...	...	...
High-nickel copper	0.066	...	...	0.087	...
Nickel bronze	0.087	...	...	0.120	...
Nickel-aluminum bronze	0.082	...	...	0.126	...
Aluminum bronze	0.144	...	...	0.197	...
Aluminum	0.52[a]	...	...	...	...
Aluminum-copper-silicon	0.452[b]	0.460	...	...	...

[a] Value for room temperature. [b] Value for 25°C.

the temperature of the medium decreases at first almost linearly with distance but as the distance increases the temperature asymptotically approaches the temperature of the main body. The temperature difference between the surface and the medium and the velocity with which the medium passes over the surface are factors regulating this type of heat flow. The greater either of these factors is, the greater will be the heat flow.

In heat transfer by natural convection the position of the hot surface with regard to the establishment of convection currents is important. A horizontal surface with heat loss downward will not lose as much heat by convection as if the heat flow were upward from the surface.

Heat Dissipation Equation.—There is no general equation for heat transfer by convection. A number of equations have been formulated but each is applicable only for special conditions. In the case of heat transfer by natural convection it has been shown by a number of investigators that the heat lost is proportional to the 5/4 power of the temperature difference between the surface and the medium thus

$$q = B(\Delta T)^{5/4} \qquad (8)$$

where

q = Quantity of heat flow per unit area per unit time
ΔT = Temperature difference
B = Constant, depending on existing conditions

For forced convection it has been found that the heat loss by convection is proportional to $\sqrt{V}$ for small wire and to V for large bodies, V being the velocity of the medium.

Radiation

Laws Governing the Radiation of Heat.—In heat transfer by radiation the terms *black body* and *emissivity* are frequently used. A black body is one which absorbs and emits all radiation of all wave lengths falling upon it as a result of temperature and reflects none. Emissivity is the ratio of the radiant energy emitted per unit time and area by a body to that emitted by a black body at the same temperature. The emissivity used in heat transfer is called total emissivity distinguishing it from spectral emissivity used in dealing with monochromatic radiation.

The fundamental law for heat loss by total perpendicular radiations is the result of both experimental and theoretical work. This law known as the Stefan-Boltzmann law is

$$q = CA(T_1^4 - T_2^4) \qquad (9)$$

where

q = Cal./sec.
A = Area cm.^{2}
T_1 = Temperature (°C. abs.) of the radiating surface. (Kelvin Scale)
T_2 = Temperature (°C. abs.) of the irradiated surface
C = Constant = 1.37×10^{-12} cal./cm.^{2}/sec./°C. abs.

In practice most surfaces do not radiate like a black body, hence their emissivity is less than unity. By use of Kirchhoff's radiation law and the Stefan-Boltzmann equation the total perpendicular radiation loss from a non-black body is

$$q = CA\epsilon(T_1^4 - T_2^4) \qquad (10)$$

where ϵ = emissivity.

If the heat flow takes place between two parallel surfaces the emissivity of equation *10* is

$$\epsilon = \frac{\epsilon_1\epsilon_2}{\epsilon_1 + \epsilon_2 - \epsilon_1\epsilon_2} \qquad (11)$$

where

ϵ_1 = emissivity of one surface
ϵ_2 = emissivity of the other surface

The heat loss by total perpendicular radiation as given by equation *10* is of interest in most practical cases. By use of Lambert's radiation law and equation *10* the radiation loss in any given direction is

$$q_d = \frac{CA\epsilon(T_1^4 - T_2^4)}{\pi} \cos\phi \qquad (12)$$

where q_d = radiation loss in the direction making an angle ϕ with the normal to the radiating surface.

Equation *12* does not hold for polished metal surfaces as these generally show greater radiation in an oblique direction than perpendicular to the surface.

Surface Conditions and Coefficients.—The emissivity of a body results in part from surface conditions. In general for a given metal the more highly polished the surface is the lower will be its emis-

sivity. The total emissivities of some metals are given in Table 6.

Table 6—Total Emissivity of Some Metals[a]

Metal	Surface Condition	Temperature, °C.	Total Emissivity
Iron	Unoxidized	100	0.05
	Oxidized	100	0.74
	Oxidized	500	0.84
	Oxidized	1200	0.89
	Rusted	25	0.65
Steel	Unoxidized	100	0.08
	Oxidized	25	0.80
	Oxidized	200	0.79
	Oxidized	600	0.79
55Fe-20Ni-25Cr	Oxidized	200	0.90
	Oxidized	500	0.97
Copper	Unoxidized	100	0.02
	Oxidized	200	0.6
Monel	Oxidized	200	0.43
	Oxidized	600	0.43
Aluminum	Unoxidized	25	0.022
	Unoxidized	100	0.028
	Unoxidized	500	0.060
	Oxidized	200	0.11
	Oxidized	600	0.19

[a] Values given for oxidized surfaces are uncertain by 10 to 30%.

Relative Importance of Conduction, Convection and Radiation

In the dissipation of heat from a completed weld, the thermal conductivity, or better the thermal diffusivity, which is equal to the thermal conductivity divided by the product of the specific heat and density, is the factor besides temperature gradient governing the flow of heat in the metal to the surface. Convection and radiation are the means of transferring the heat from the surface to the surrounding medium. The greater the temperature difference between the weld and the medium, the greater will be these heat losses per unit time provided sufficient heat from within the weld reaches the surface in the same time.

For very calm air the heat loss by radiation is greater than by convection for all temperatures of the weld. When air is blowing over the weld with a velocity of 10 meters per second the heat losses by radiation and convection are about equal at approximately 500°C. At higher temperatures the heat loss by radiation is greater and the difference in heat loss by radiation and convection increases rapidly with temperature. Below approximately 500°C. the heat loss by convection is greater. The curves show in this case that at 100°C. the heat loss by convection is about five times that lost by radiation.

Thin Sections.—In a thin section the thickness of metal through which the heat is conveyed to the surface is small and hence the resistance to heat flow to the surface is small. The ratio of surface area through which heat is lost to the volume of metal present is relatively large. The heat loss from this type of welded section is governed principally by the factors influencing loss by convection and radiation.

Heavy Sections.—Heat from within a heavy section has to go farther to reach the surface than does the heat from within a light section. The rate at which it reaches the surface depends upon the thermal diffusivity of the metal and the temperature gradient between the surface and the interior of the metal. The rate of heat dissipation from this type of welded section depends not only upon convection and radiation but also upon the thermal properties of the metal. Protection may or may not be required during the cooling of such a weld, depending upon its metallurgical characteristics.

In almost all types of welding the most important factor governing the dissipation of heat from the weld area is conduction. This is due to the steep thermal gradients adjacent to the weld which result from the localized application of heat. This is very different from the case of an entire metallic body heated to a uniform high temperature. The effect of rapid cooling by conduction is accentuated in the case of heavy plates welded with small electrodes, due to the relatively large path through which heat may escape from the weld area and the large heat reservoir provided by the heavy plate.

Thermal Conductivity.—The thermal conductivity or better the thermal diffusivity of the metal in a weld is a factor along with temperature gradient and the geometry of the metal, which determines the rate of heat flow from the interior of the metal to the surface. Metals with the higher thermal conductivities generally have higher diffusivities. The thermal conductivities of iron, aluminum and copper are, respectively, 0.19, 0.52 and 0.92 and in the same order thermal diffusivities are 0.22, 0.85 and 1.12, both properties being expressed in cgs. units. With the same conditions of temperature gradient, geometry and ability to lose heat to the surrounding medium, the metal with the

higher thermal diffusivity will dissipate heat from a weld at a greater rate than a metal with a lower thermal diffusivity.

Reversible Heat

During the heating of a metal to its fusion temperature, some of the heat is dissipated as described above. Additional heat must also be supplied to bring about transformation and actual fusion. This is known as reversible heat, since it is not lost during the heating operation, but only changed to another form, from which it will be restored upon subsequent cooling.

One gram of iron at 25°C. requires approximately 316 calories for melting. Approximately 70 calories of this required heat are in the form of reversible heat, that is, heats of transformation and fusion. Thus in melting iron for welding about 22% of the heat required is in the form of reversible heat. The heat of transformation at the A_3 point is 3.63 calories per gram and at the A_4 point 1.7 calories per gram. The heat of fusion is given as a round figure of 65 calories per gram.

Similar data for steel are not available excepting values for the heat of transformation at the A_1 point in a eutectoid steel for which one suggested value is 15.9 calories per gram. Considering this value and the heat of fusion, approximately 25% of the heat required in melting steel for welding is in the form of reversible heat.

MECHANICAL PROBLEMS

Expansion and Contraction

The most common and widely known effect of temperature upon metals is expansion on heating and contraction on cooling in all three directions: length, width and thickness. As an example, Curve A, Fig. 5, represents the increase of length, in percent of initial length, of a mild steel, grade SAE 1020, when heated above the room temperature. The increase is nearly linear and amounts to almost 1% at 1200°F.

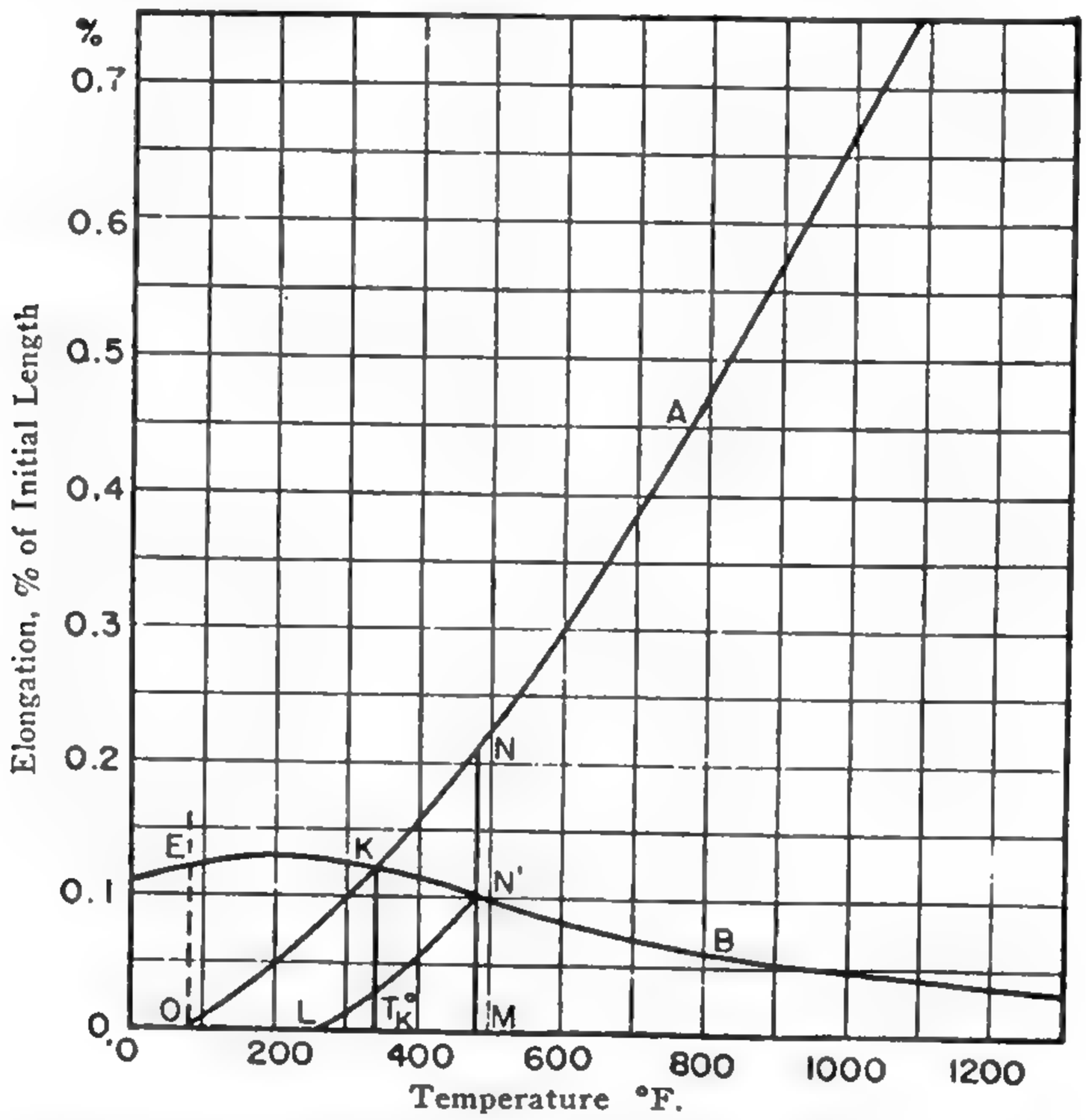

Fig. 5.—Thermal Elongation and Elastic Limit Curves as a Function of Temperature for Plain Low-Carbon Steel, SAE 1020

Since welding is a local operation, the extent to which the metal will be heated and thereafter cooled will be very limited. Consequently there will be little possibility of free expansion and contraction. *Be-*

cause of this a state of constraint will be originated in weldments, and this constraint is expressed most conveniently in terms of stresses. There is no external load applied to the object and these stresses may or may not disappear when room temperature is restored. Stresses produced during local heating will be referred to as *thermal stresses.*

The stresses which develop in a weld and welded structure are of two types:

1. *Residual stresses* which are the result of shrinkage of metal on cooling, metallurgical changes or plastic deformation at elevated temperatures of adjacent sections of the weld and base metal. They occur in all three dimensions with both free and restrained base metal and may be regarded as being due to the restraint of the movement of one part of the base metal or weld by other parts.
2. *Reaction stresses* which are the stresses within the assembly under consideration due to the stresses between that assembly and the rest of the structure. For example, a tensile stress will develop across a welded butt joint during cooling if the normal thermal expansion and contraction are prevented by external transverse restraint.

Factors Favoring the Production of Residual Stresses

As stated previously, residual stresses may or may not occur when the heated part has been brought back to its initial temperature. Thus, heat input alone is not sufficient to promote their existence. In fact, residual stresses may be created without any heating at all being involved in the process. For example, residual stresses may readily result from any machining or forming operation.

It has become common knowledge that rolling sets up important residual stresses in large I-beams. It has also been pointed out repeatedly that cold working is responsible for creation of residual stresses in deep drawn brass tubes. Furthermore, there is ample evidence that milling and grinding may leave the surface of the metal under considerable compressive stress.

While it is not the purpose of this chapter to deal with processes other than welding, it may be said that, as a general rule, the occurrence of residual stresses is essentially connected with *permanent set* taking place during some operation.

With respect to the residual stresses set up by heating the following factors are essential:

1. Thermal expansion.
2. Non-uniform temperature distribution.
3. Local, permanent (plastic) deformation.

All three conditions are necessary to promote residual stresses, because (1) no constraint, and consequently no residual stress, is possible without thermal expansion. That is why quartz, whose thermal coefficient is practically zero, may undergo safely any drastic change in temperature despite its high brittleness; (2) if a body is heated and cooled uniformly, there can be no reciprocal constraint due to thermal expansion and consequently no residual stress; and (3) if the body suffers no permanent (plastic) strain during the whole thermal cycle, then the strain, being only elastic, must disappear when the initial temperature is restored.

According to this principle, a material which remains entirely elastic, up to the breaking point, will never retain any residual stress. It may eventually fail, if the heat input imposes upon it a stress which exceeds the ultimate strength. Under usual working conditions mild steel and most of the structural metals exhibit considerable plastic yield before breaking, and this is exemplified by the usual stress-strain diagrams of mild steel SAE 1020, in tension, Fig. 6.

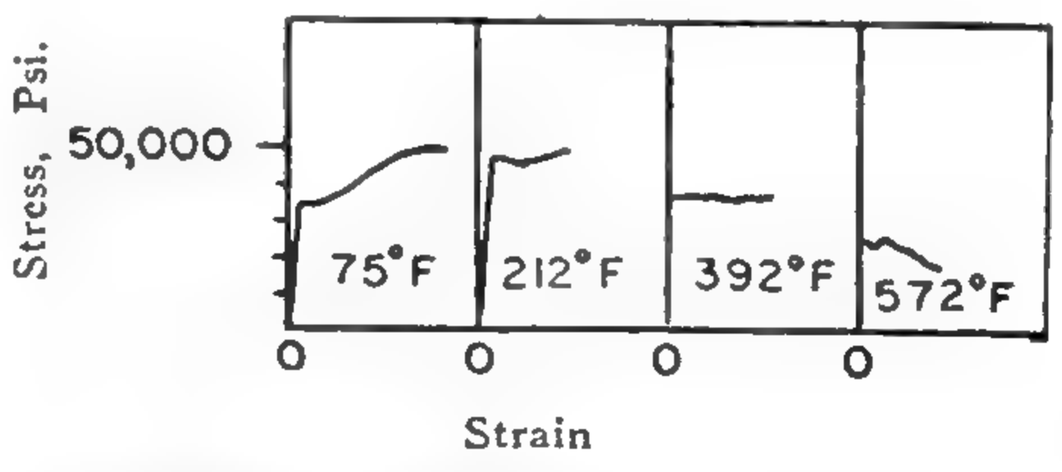

Fig. 6.—Stress-Strain Diagrams for Plain Low-Carbon Steel, SAE 1020, at Various Temperatures

At room temperature the strain remains purely elastic only up to about 0.1% elongation. When the stress exceeds only slightly the elastic limit, the strain suddenly becomes plastic and, with little or no increase in stress, may increase to more than ten times its value just below the elastic limit.

A similar trend is exhibited at higher temperatures, as shown in Fig. 6, but the maximum elastic strain is not the same; at first it increases with temperature up to 350°F., then it decreases rapidly. Above 900°F. there is no longer a definite elastic limit because of creep phenomena, and it is doubtful whether there can be any elastic strain at all above 1200°F. If the values of the maximum elastic strain are replotted curve B of Fig. 5 is obtained. It is seen that this curve intersects Curve A at the point K which corresponds to the temperature $T_K = 340°F$. Below this temperature the thermal expansion is smaller than the strain at the elastic limit; above this temperature it is greater than the elastic strain.

The exact location of the temperature T_K is important for the occurrence of residual stress. For, as will be seen later, no residual stress can ever occur if the highest temperature during the thermal cycle lies below the temperature T_K. Nor can any possible change in shape or dimension take place after the cooling is completed, *provided the material was stress-free at the start.* Unfortunately, not only is the temperature T_K different for different materials, but there is good reason to believe that it may change with the state of stress imposed upon the object. Although more experimental work is needed to secure reliable information on this point, it may be assumed for the present that Curve B is valid when the specimen is submitted to compression instead of tension. Of course, the values will be negative instead of positive.

With this in mind, it will be shown that, if all of the three previously mentioned conditions are present, residual stress may occur due to heat input.

For the sake of simplicity, let us consider the assembly represented in Fig. 7. It consists of a bar, A, inserted into a frame. We shall assume that the assembly is of mild steel SAE 1020. Upon heating, the bar A would expand according to the Curve A. Fig. 5, if removed from the frame, and this fulfills Condition 1. Furthermore, if the bar A alone is heated while kept inserted in the frame, Condition 2 will be also fulfilled.

Now, it will be assumed for the sake of simplicity that the frame is rigid enough to prevent any deformation of the bar. Thus, the thermal expansion, ϵ_t, will have to be cancelled by a mechanical compression, $-\epsilon_m$, resulting from the reaction of the frame. We may thus write

$$\epsilon_t - \epsilon_m = 0 \qquad (13)$$

From the diagrams, Fig. 5, it follows that up to the temperature T_K the mechanical strain ϵ_m will be purely *elastic.* Therefore, if from T_K or any lower temperature, the bar is cooled back to room temperature, no residual strain will be left in the assembly. But above the temperature T_K, say at M, the thermal expansion $\epsilon_t = MN$, is greater than the available maximum elastic compression, $-\epsilon_e = N'M$. Consequently, the bar A must undergo a plastic deformation, $\epsilon_p = NN'$, of sufficient amount to cancel the thermal expansion ϵ_t. In other words,

$$\epsilon_t - \epsilon_e - \epsilon_p = 0 \qquad (14)$$

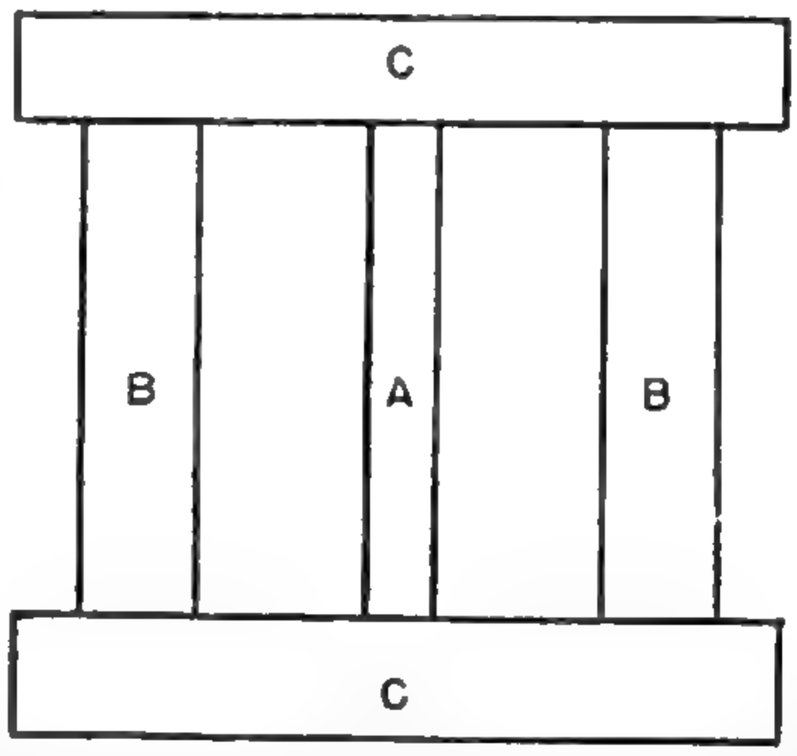

Fig. 7.—Illustrations of How Thermal Elongation, Non-Uniform Heating and Plastic Deformation Create Residual Stresses

The existence of plastic flow ϵ_p fulfills the third condition, and it is easy to see that now bar A will retain some residual tension when cooled down to room temperature. For, if left free, the bar would become shorter by the amount NN', and to prevent the contraction the frame must submit the bar to a strain of opposite sign; i.e., to an elongation equal to NN'. If NN' is smaller than the elastic strain, OE, at room temperature, the residual stress, S_r, will be equal to $NN' \times E$, where E is the modulus of elasticity.

If NN' is greater than the maximum elastic strain, OE, at room temperature, a part of the residual strain will become plastic and the residual stress will be practically equal to the elastic limit.

Similar conditions prevail in welding. Any welding process involves definite expansion, non-uniform temperature dis-

tribution and local plastic flow. Two butt-welded plates exert upon the weld the same action as the frame upon bar *A* by preventing the weld from shrinking longitudinally. Hence, residual stress is almost unavoidable in welding. However, the reciprocal influence between the heat-affected and non-affected part of the weldment is not exactly that of a heated bar inserted into a rigid frame. First, this mutual influence is exerted not only in one direction but in all three directions. Furthermore, unlike the rigid assembly, the welded object as a whole may undergo some general residual distortion, and it is of interest to know how this last modification would affect the residual stress.

To make it clearer let it be assumed that the assembly in Fig. 7 is no longer rigid and that each of the two columns has the same cross-section as the bar *A*, equal to one square inch. Then the bar will be only partially restrained from contracting, and the amount of contraction which will actually occur will place the columns in compression. If the yokes, *CC*, are rigid, the contraction must be the same for the bar and columns. There must also be an equilibrium of stresses.

From these two conditions the magnitude of the stresses and the amount of plastic flow of the bar may be computed if the amount of general contraction is known.

As an example let us assume that the amount of contraction which places the columns in compression is —0.03%. Then each of the columns is submitted to a residual stress.

$$S_c = \frac{-0.03}{100} \times E \cdot$$

where E is the modulus of elasticity equal to 30,000,000 psi. Hence

$$S_c = \quad 9000 \text{ psi.}$$

The total compression upon the columns will be found as a product of S_c and the cross-section of the column (2 sq. in.) = 18,000 lb. This *compression* is balanced by an equal *tension* acting upon the bar.

Hence the residual tension in the bar (cross-section = 1 sq. in.) = +18,000 psi., and the corresponding strain = 18,000/30,000,000 = +0.06%.

Because of the tension strain, the bar has been unable to contract more than 0.03% assumed previously.

Thus, the total contraction which would have occurred, if the bar had been able to shrink freely, is:

$$0.03\% + 0.06\% = 0.09\%$$

This total contraction represents the plastic flow undergone by the bar during the heating cycle.

The consideration of this simple case suggests that, if the amount of shrinkage undergone by the object during welding is known, it is possible to compute the amount of residual stress on the basis of the law of equilibrium of forces, and also to determine the amount of plastic flow involved in welding. Conversely, the knowledge of the amount and extent of plastic deformation in welded objects should permit the computation of the amount of shrinkage and residual stress on the basis of the law of continuity of deformation and equilibrium of forces.

Now consideration of Fig. 5 suggests that the amount of plastic deformation is dependent upon the maximum temperature reached during heating.

In this way the whole problem of residual stresses would be based really upon the knowledge of heat distribution during welding.

An attempt to derive the distribution of residual stresses from the distribution of temperature during welding has shown that in simple cases a good approximation has been obtained, at least in points which were located not too close to the weld. It is doubtful whether this procedure would yield more than a qualitative picture in more complicated cases.* The plastic behavior of the material under two- and three-dimensional states of stress, such as are encountered in actual welding, is far from being known, and without this knowledge the relation between stress and strain can be merely a matter of speculation.

For example, sometimes it has been stated that the greater the distortion the smaller are the residual stresses. This statement is mostly based upon consideration of elementary cases like that offered by the assembly of Fig. 7. If this assembly underwent no shrinkage whatsoever, the whole plastic deformation of

* It may, however, be useful in predicting the sign and the probable location of maximum residual tension. As a rule, the part which is the last to cool to room temperature will also be the one submitted to the highest residual tension.

the bar in the previous example, 0.09%, would be cancelled by the elastic strain which would increase the residual stress from 18,000 to 27,000 psi. In actual practice there is no assurance that residual stresses are less when distortion is present. While distortion is always the result of stresses, and in most cases the stresses probably are lessened by the distortion, one should not draw the conclusion that distortion is evidence that the residual stresses are low. Likewise it is just as important to remember that absence of distortion is no proof of the presence of residual stresses.

Distribution and Magnitude of Residual Stresses

It is impossible to make general statements which will cover the distribution and magnitude of residual stresses. However, certain statements regarding specific conditions can be made.

The most common weld is a simple butt weld between two unrestrained plates of finite size. The pattern of the residual stresses for such a weld is well known. The longitudinal stresses approach in value the yield strength of the deposited weld metal, which is usually greater than the yield strength of the base plate. The transverse stresses are low tension except at the ends where they become rather high compression.

Since the longitudinal residual stresses are at the yield point, they are not increased by external restraint. If, however, external restraint is applied in the transverse direction, the transverse stresses will increase with the yield strength of the plate material as their limiting value.

The longitudinal stresses are a function of weld length and plate thickness. In ordinary low-carbon steel plate, 1-in. thick, the longitudinal residual stresses have a maximum of 47,000 to 50,000 psi. In $^{3}/_{4}$-in. thick plate of the same material their maximum is only 40,000 to 42,000 psi.

In all welds the stresses tend to be tri-axial in nature. However, except in very thick plates the stresses in the third direction are minor so that the stress system is essentially two-dimensional. Theoretically, the ability for plastic flow to occur should be materially reduced when tri-axial stresses exist. However, in weldments having serious restraint in three directions, tests have shown that enough plastic flow does occur to wipe out or reduce the residual stresses. Therefore, there is no direct evidence that even in structures where there is considerable tri-axiality of stresses do residual stresses do any harm.

Importance of Residual Stresses

There has been much discussion regarding the effect of residual stresses. Extensive tests have shown that where plastic flow can occur, even as little as $^{1}/_{2}$%, residual stresses have no effect upon the performance of structures subjected to static loading. Even in very rigid structures which had a high degree of tri-axial restraint, residual stresses had little or no effect. Whether a load can be applied to a structure so rapidly that there would not be time for a small amount of plastic flow to occur, with the result that residual stresses would have injurious effects, is questionable. The effect of residual stresses upon structures subjected to dynamic loading and upon fatigue strength is not known with certainty. There is some evidence that they have a harmful effect under these conditions, but the results as yet are not conclusive.

Control of Residual Stresses

The extent to which residual stresses may be controlled during welding is very limited. Extensive tests have shown that wide variations in welding sequence result in longitudinal residual stresses of almost the same magnitude. In most cases even the stress pattern is changed only slightly.

Certain block welding sequences will reduce the residual stresses to some extent. However, if the procedure results in the final block being put in under a condition of high restraint, high residual stresses will result in this block. If welds can be kept short, the residual stresses will be low. This is seldom possible.

If welds are located at points which possess the least rigidity, the stresses will be kept to the lowest possible magnitude. Figure 8 illustrates this point.

In a few cases it is possible to reduce the magnitude of reaction stresses by mechanical or thermal control. Consider the column assembly shown in Fig. 9. If Column *A* were removed from the as-

sembly and welded, there would be no reaction stresses and very little residual stresses. If the weld is made while *A* is in the assembly, as shown in Fig. 9, the restraint offered by the axial shrinkage involved by welding is 0.06% of the whole length. If the assembly is made of mild steel, at room temperature this amount of deformation is still within the elastic range. Consequently the columns *BB* may be safely expanded to this extent by any mechanical means, for example,

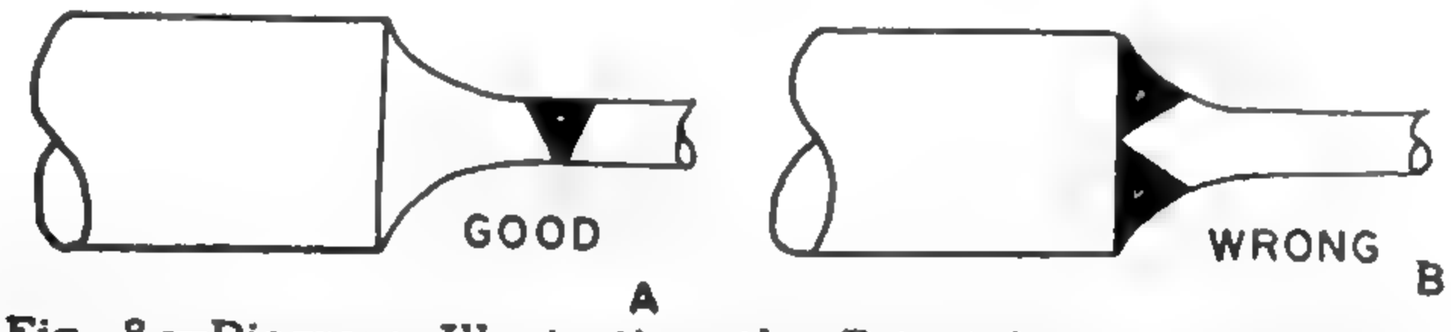

Fig. 8.—Diagram Illustrating the Principle of Avoiding the Locating of Welds in Highly Stressed Structures at Points of Important Change of Section

by lifting jacks; they will recover their initial length after removing the jacks. If the repair welding is being made while the columns *BB* are under constraint, then *after complete cooling of the weld* the removal of the jacks will cause the same

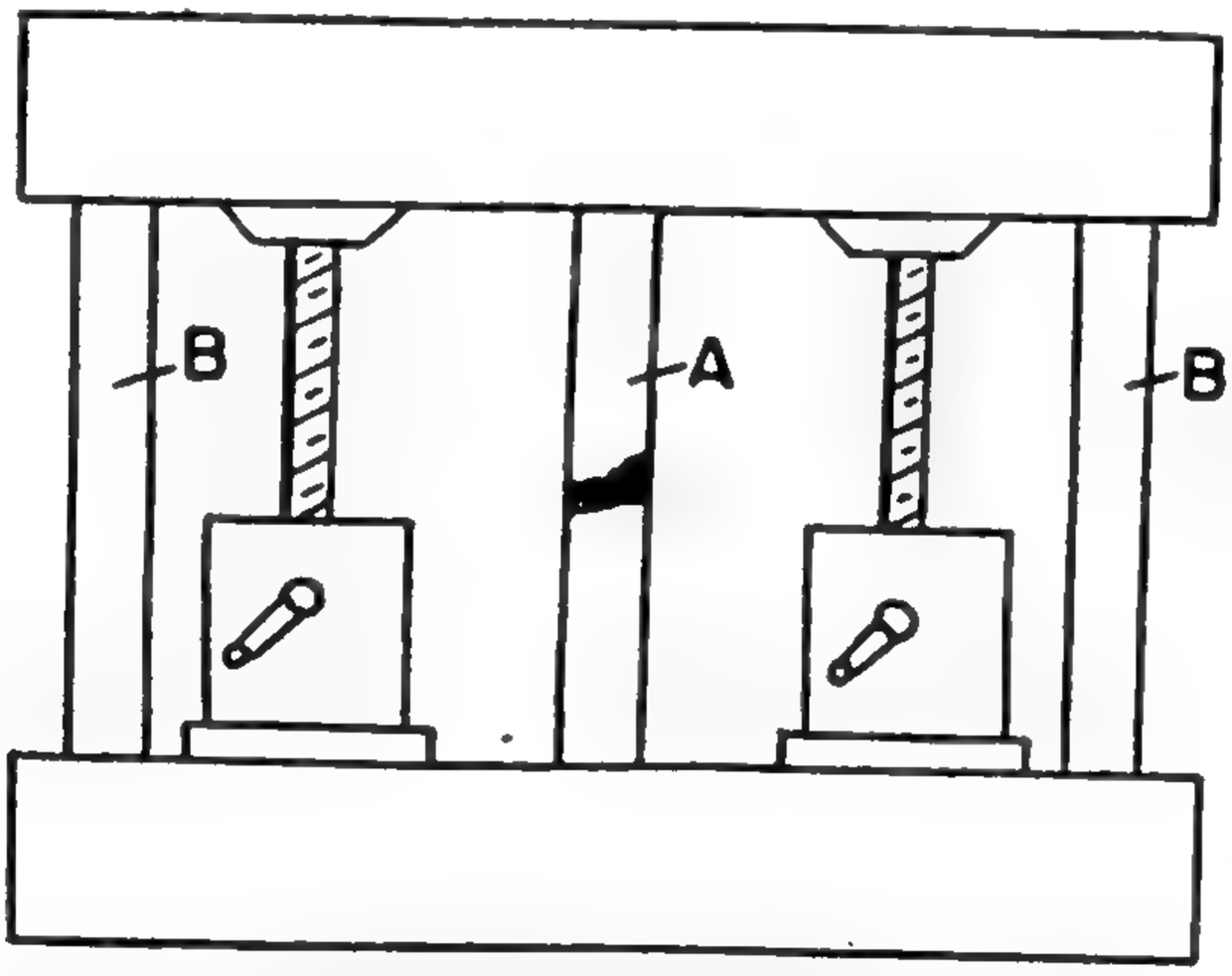

Fig. 9.—Semi-Rigid Frame, Illustrating the Mechanical Control of Residual Stresses by Deformation of Structure Before Welding

contraction in all three columns, and no reaction stress will be left in the assembly.

The same purpose can be achieved by *preheating* the columns *BB* to some 220° F., at which temperature the expansion will be equal to 0.06% (Fig. 5). The cooling of the *columns BB must not take place* before the weld is completely cooled; otherwise, some reaction stresses will develop. For it is seen from Fig. 5 that above room temperature, say at 180°F., there still remains a great deal of shrinkage to take place in cooling to room temperature, and consequently high reaction stress may occur. There is no reason why this stress should disappear if all three columns are cooled *simultaneously* down to room temperature.

Consideration of Fig. 5 suggests that no shrinkage and no reaction stress will develop at any intermediate temperature thereafter, if the three columns are simultaneously cooled from the temperature marked by letter *L* in Fig. 5, at which temperature the shrinkage is exactly zero. Owing to the fact that the metal adjacent to a weld reaches all possible temperatures between the melting point and the surrounding plate temperature, it will not be possible to find a temperature corresponding to the letter *L*, at which the shrinkage will be exactly zero, except possibly for parts which reach a very high temperature. In welding, this temperature will be generally found above some 1200°F. so that this

treatment will become equivalent to a stress-relieving heat treatment.

Relief of Residual Stresses

Since residual stresses nearly always are present in weldments, there is often a desire to remove or reduce them. This is accomplished only by forcing or allowing plastic deformation to take place in such a way that its effect will be opposite to that of the shrinkage. The actual methods by which residual stresses may be relieved or reduced are discussed in Chapter 43.

Shrinkage and Distortion

The factors responsible for shrinkage distortion are basically the same as the factors favoring residual stress which have been considered previously. But there is no simple relation between shrinkage distortion and residual stress. By shrinkage distortion is meant the overall change in shape and dimension caused by welding. In special cases this change may be insignificant, yet residual stress may be high, if, for example, the parts to be welded are firmly held everywhere during welding. Conversely, great apparent distortion may be connected with only small residual stress, if welding is made on highly preheated parts, which are easily deformed.

The extent and amount of shrinkage distortion are widely dependent on the orientation and geometry of welds.

As a rule shrinkage will be smaller in the *direction* of weld than *transverse* to the weld, because in the longitudinal direction differently heated zones will be more in conflict than in the transverse direction. However, high transverse rigidity may easily upset this rule. In neither case will the shrinkage become very important. For example, the overall shrinkage is reported to be: (1) 0.1% in arc-welded plate girders; (2) 0.05% in arc-welded lattice trusses; (3) 0.03 to 0.04% in welded ships, in length. This is no longer true when the welded structure undergoes *buckling* or angular *distortion.*

Angular distortion is a result of an unsymmetrical shrinkage. It may become important if the structure offers little rigidity in the direction in which the angular distortion is going to take place. This is particularly true if the shrinkage is not uniform across the *thickness.* Consider, for example, in Fig. 10, a butt-welded joint made in several passes. After the first bead has been laid and cooled down to room temperature, the joint will no longer be able to shrink freely in the transverse direction. Thus, the shrinkage of the second layer will be impeded by the resistance of the first layer, and since these two actions are not in line, angular distortion will result. Angular distortion will increase gradually as welding proceeds, provided the subsequent beads are deposited in the same way as the second one. Likewise, a bead deposited on the upper face of a plate will tend to make the plate curl and buckle in the longitudinal direction, Fig. 11.

Fig. 10.—Sketch Illustrating the Tendency of Multiple-Pass Welds to Produce Distortion

Unsymmetrical shrinkage with respect to the *width* may also cause angular distortion. So, for example, marked curvature may occur in composite beams having continuous fillet welds located eccentrically with respect to the gravity axis, x—x, Fig. 12.

Finally, unsymmetrical shrinkage in continuous welding *along* the seam is revealed by gradual closing of the space between two butted plates. Methods for the control and removal of shrinkage and distortion are given in Chapter 43.

HEAT FLOW PROBLEMS

Particular Features of Heat Flow in Welding

Compared to other problems of heat flow in bodies, the problem of heat distribution during welding (and oxygen cutting as well) exhibits two particular features: first, the *heat source* (arc in

arc welding, torch in gas welding) instead of being stationary moves on the surface of the piece to be welded with a speed which is usually constant; second, if welding is performed over a sufficient length, a state called *quasi-stationary* is soon created in the weldment.

To define this state let us assume an observer to be stationed at the source of heat during welding. Then, if the quasi-stationary state is reached in the piece, the observer will notice no change in the

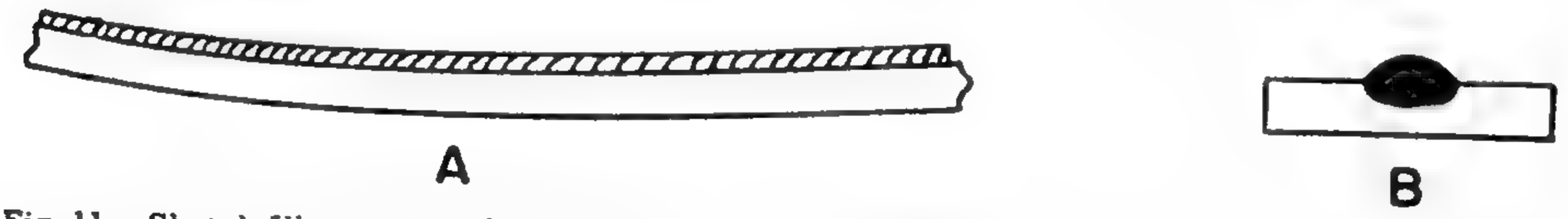

Fig. 11.—Sketch Illustrating the Effect of Longitudinal Weld Shrinkage in Producing Distortion

temperature distribution around the heat source. To look at it in another way, let the temperature distribution around the heat source be represented by a hill, the isotherms being the contour lines of the hill (lines in Fig. 13); then, in a quasi-stationary state of heat transfer the hill will move as a rigid body on the surface of the plate without undergoing any modification either in size or shape.

As a consequence the traces left on the surface by different isotherms will become straight lines parallel to the direction of welding.

The establishment of the quasi-stationary state can easily be demonstrated by means of the zones of different color, which form on the polished surface of a steel during welding. As is well known, these colors are formed at definite temperatures so that the maximum temperature reached by different parts of a plate can be determined. When the thermal state is quasi-stationary, these zones become parallel to the direction of welding.

Theoretical Approach

The establishment of a quasi-stationary state can be accounted for by the general equations of heat flow. A solution is then obtained with the desired degree of precision for most practical cases. However, the usual assumption is involved in such a solution, namely, that the physical characteristics of the material such as specific heat, density and heat conductivity are independent of the temperature. As previously seen, this assumption is by no means true, and a correcting factor will be generally needed to adjust the formula to experimental results.

To simplify the calculations two additional assumptions are made:

1. The heat source is a point. This assumption is satisfactory for arc welding with small electrodes, but is only a rough approximation for gas welding and cutting.

2. From large welded pieces there are no heat losses to the surrounding atmosphere. In general, this assumption is supported by experiment, and is explained by the fact that the heat conductivity of metals is usually much greater than their heat transmission through the surfaces. This may not be true for certain special steels with low conductivity, but, even for these, the assumption is advantageous because

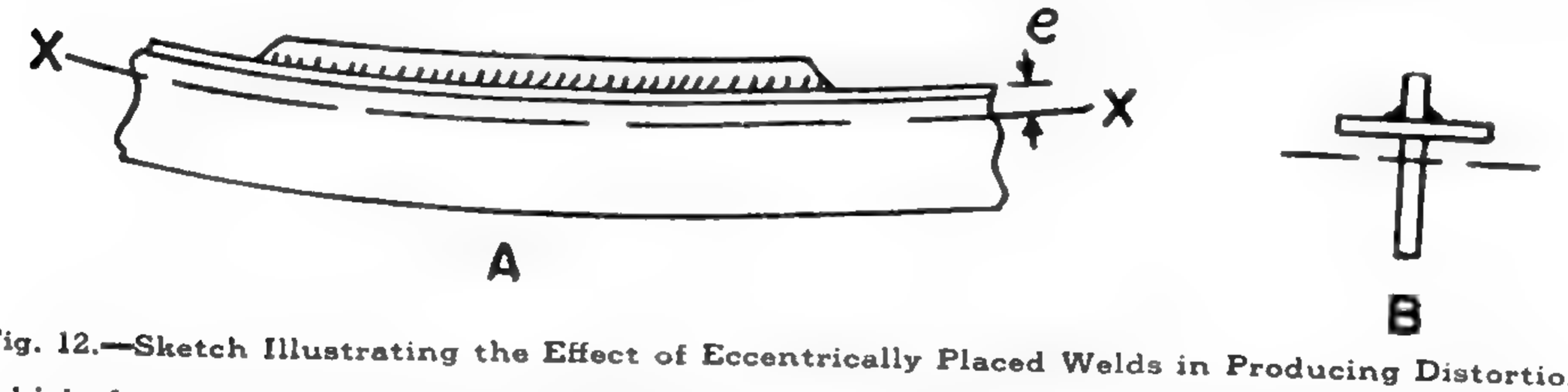

Fig. 12.—Sketch Illustrating the Effect of Eccentrically Placed Welds in Producing Distortion

it enables an investigator to account separately for the influence of each factor, which is sometimes difficult in an experimental study.

Practical Results

The heat distribution of the quasi-stationary state during welding is best understood when examining families of isotherms drawn around the heat source, Fig. 13. The general features of heat

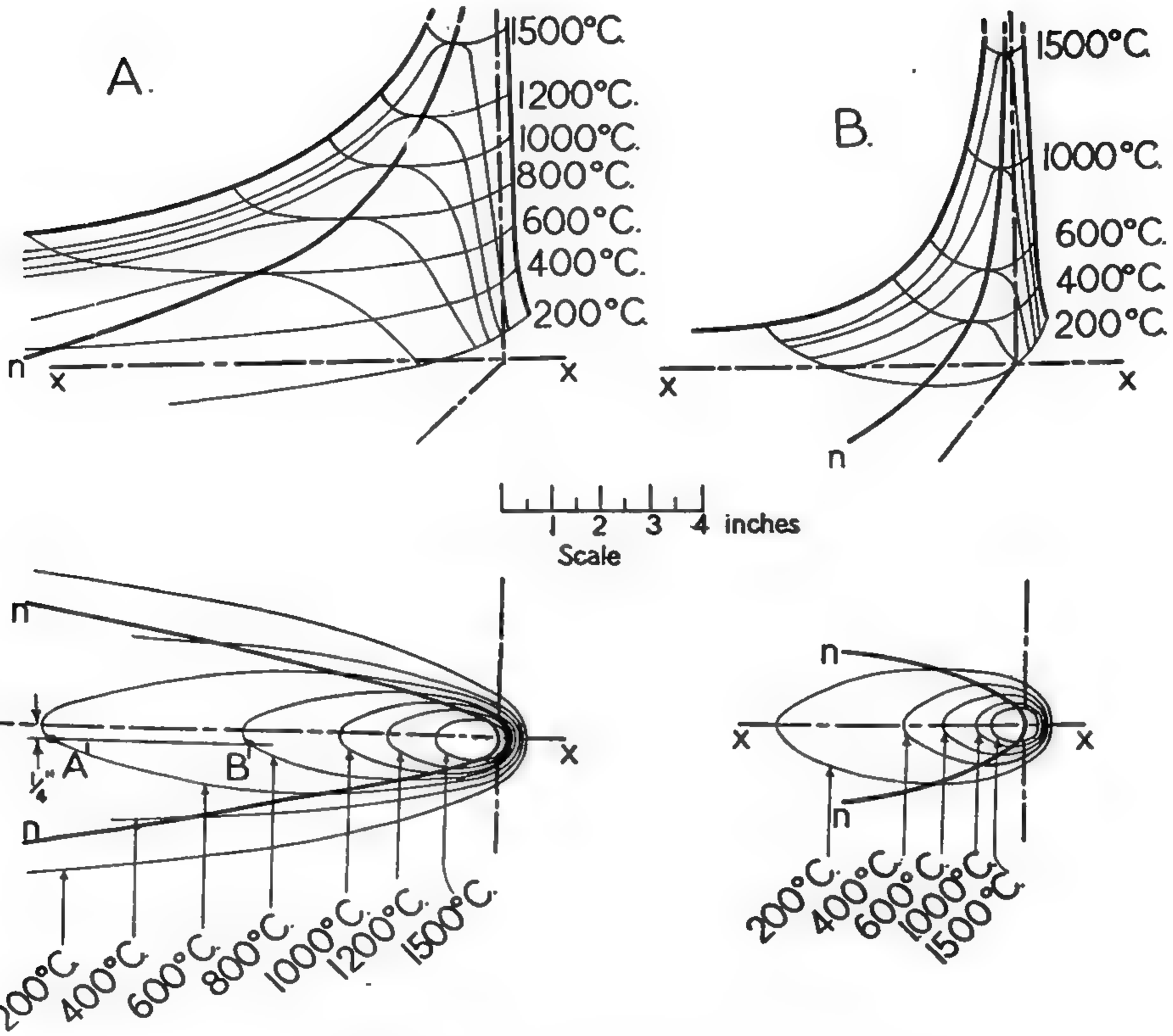

Fig. 13.—Temperature Distribution Around the Heat Source

(Left) Thin plate (0.2-in. thick). (Right) Very thick plate (more than 4-in. thick).
(Top) Representation in form of a hill. (Bottom) Representation in topographic projection.
n–*n*—Locus of maximum temperature.
Plate—low-carbon steel; current intensity, 200 amp.; welding speed 8.0 in./min.

flow involved in welding are at once apparent from these isotherms, namely:

1. The rise of temperature, in front of the heat source, is steeper than the fall of temperature behind the source.

2. The points on the plate passing through the maximum temperature at the same instant are located on a line, *n*, which is curved backward. This is due to the finite speed of heat flow in metals, which delays the occurrence of the maximum temperature in parts of the plate more distant from the weld seam. The curve *n* separates the part of the plate (in front of it) with temperature rising, from the part (behind it) with temperature falling at the same instant.

3. As a consequence of a much steeper temperature gradient ahead of the electrode during welding, brought about by the movement of the heat source relative to the direction of heat flow, the metal is more quickly heated to, than cooled from, a given temperature. The difference is particularly pronounced at the line of welding and it decreases gradually for the more distant portions of the plate.

The influence of each factor is also explained more readily by comparison of the corresponding isotherms:

1. *Thickness.*—As shown in Fig. 13 for welding conditions in which there is the same rate of heating, a wider heat-affected zone is created in the thinner plate (thickness—0.5 cm. = 0.2 in.) than in the thicker one (of almost infinite thickness). As a result the temperature drop (gradient) is less pronounced in the former one. At the same time the lag of the curve *n* is greater, this owing to the smaller cross-section and consequently greater resist-

ance offered to heat flow. (The electrical analogy is obvious.)

2. *Nature of Material.*—The two lower diagrams, Fig. 14, indicate that greater heat diffusion in aluminum, *D*, results in a more circular shape of isotherms than in iron, *C*. The same applies to the curve *n*, which, as ought to be expected, is also nearly straight.

3. *Current Intensity*—From the two left-side diagrams, *A* and *C* of Fig. 14, it is apparent that increasing current intensity widens the heat-affected zone without much changing the shape of isotherms. On the contrary:

4. *The speed of welding* affects mostly the shape of isotherms. The higher the speed, the more elongated are the isotherms and the more pronounced the lag of the curve *n*. (Compare the two diagrams, *A* and *B*, on the top of Fig. 14.)

5. *Preheating* decreases only the range between the considered temperature and the initial temperature. Neither the shape nor the size of the isotherm is changed, but the same isotherm belongs now to a higher temperature. As a result the fusion zone, i.e., the zone comprised within the isotherm of the melting point, is widened.

Application to Welding Practice

One of the most useful applications of diagrams like that drawn in Fig. 14 consists in evaluating the time needed for a given point of the welded piece to cool down from a higher to a lower temperature. As will be seen later, this is particularly important when dealing with the problem of weldability of high-carbon or low-alloy steels.

For the present application it will be recalled that in the quasi-stationary state the families of isotherms move in the direction of welding with the same speed as the electrode itself. Therefore, the

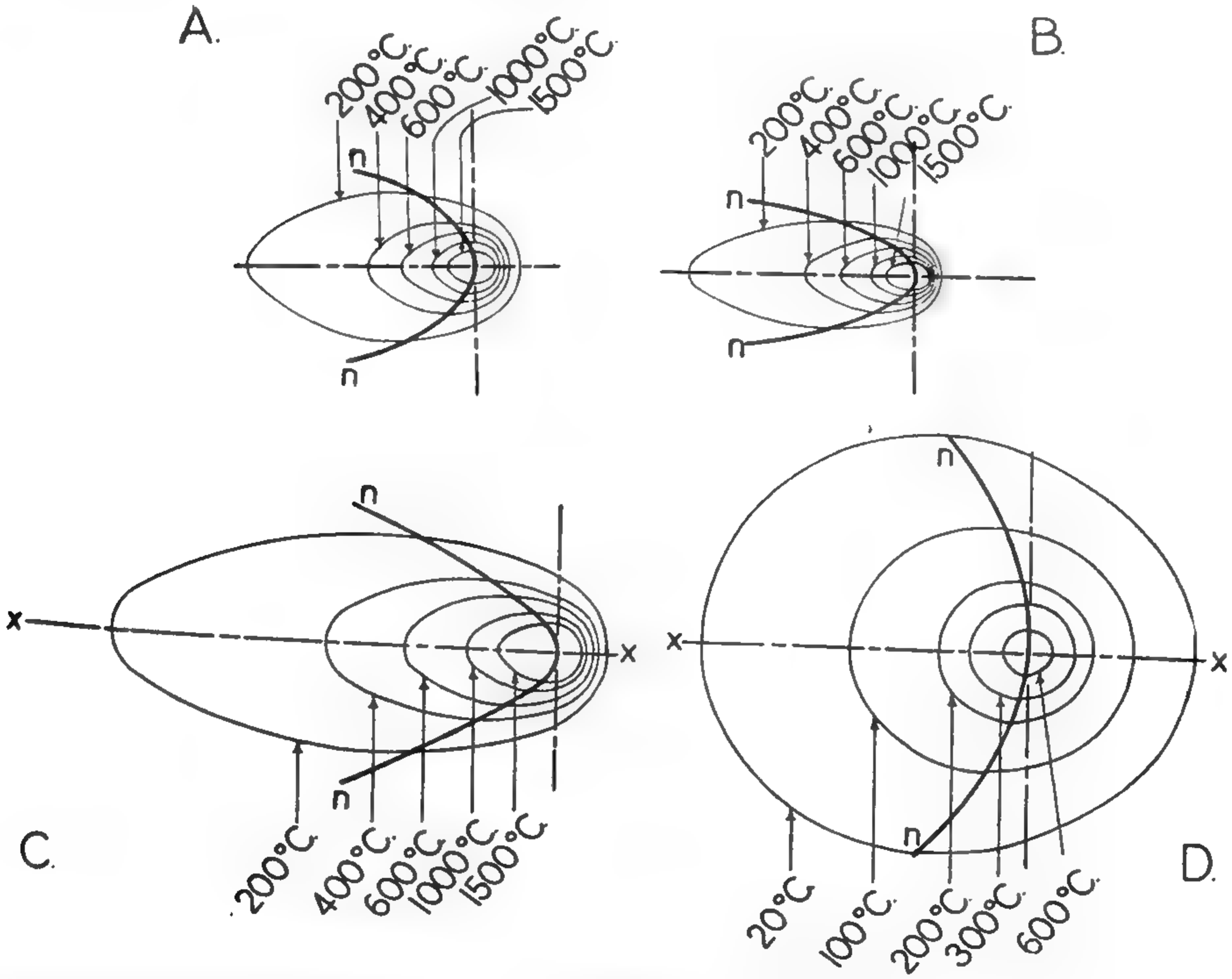

Fig. 14.—Temperature Distribution as a Function of Current Intensity, Welding Speed and Nature of the Base Metal. Very Thick Plate

A—Low carbon steel, 200 amp., welding speed, 4 in./min.
B—Low carbon steel, 200 amp., welding speed, 8 in./min.
C—Low carbon steel, 400 amp., welding speed, 4 in./min.
D—Aluminum, same heat input and same welding speed as for *C*.

time interval in which a given point of the piece is passed by two given isotherms is equal to the distance between the isotherms divided by the speed of welding.

For example, in the case of the left-hand diagram, Fig. 13, the distance between two isotherms marked 800 and 600°C. (1470 and 1110°F.) 1/4 in. away from the line of welding, X–X, is $A'B'$ = 4 in.

Since the speed of welding, v_0, is 8.0 in. per minute, the distance $A'B'$ will be covered in $A'B'/v = 4/8.0 = 0.50$ min. In other words, it would take 0.50 min. to cool any point located 1/4 in. away from the line of welding from 1470 to 1110°F. More generally, if the distance between the isotherms of Fig. 13 is read on a scale v_0 times greater in the direction of welding, the diagram, instead of marking the location of temperatures on the surface of the plate *at a given moment*, will indicate the intervals from one temperature to another for each point *of a given cross-section.*

The average cooling speed between two successive temperatures is also easily computed by means of these diagrams. Thus, in the case of Fig. 13 the average cooling speed between 1470 and 1110°F., 1/4 in. away from the line of welding, is (1470 — 1110)/0.50 = 720°F./min.

It is found that the cooling speed decreases as: (1) the heat input per linear inch of welding increases, and (2) the preheating temperature increases.

The numerical relation between these values depends upon the nature and size of specimens to be welded and also upon the welding process involved. All these influences, however, are reflected in the general aspect of the isothermal diagrams, the knowledge of which appears therefore to be of outstanding importance to the welding practice.

BIBLIOGRAPHY

1. *The Conduction of Heat,* H. S. Carslaw, Macmillan and Co., Inc., 1921.
2. *Dictionary of Applied Physics,* R. Glazebrook, Macmillan and Co., Inc., 1922.
3. *Fourier Series and Integrals,* H. S. Carslaw, Third Edition, Macmillan and Co., Inc., 1930.
4. *Industrial Heat Transfer,* A. Schack (a translation of H. Goldschmidt and E. Partridge), John Wiley & Sons, 1933.
5. *Heat Transmission.* W. McAdams, McGraw-Hill Book Co., Inc., 1933.
6. *Shrinkage Stresses in Welding,* W. Spraragen and G. E. Claussen, The Welding Journal Res. Suppl., November 1937.
7. *The Theory of Residual Stress and Strain of an Edge Welded Plate,* N. S. Boulton and H. E. Lance Martin (abstracted by W. Spraragen and G. E. Claussen) The Welding Journal Res. Suppl., November 1937.
8. *Thermal Study in Arc Welding Experimental Verification of Theoretical Formulas,* D. Rosenthal and H. Schmerber, The Welding Journal Res. Suppl., April 1938.
9. *Heat Dissipation,* W. A. Bruce, Journal of Applied Physics, November 1939.
10. *Temperature Distribution and Shrinkage Stresses in Arc Welding,* D. Rosenthal and J. Zabrs, The Welding Journal Res. Suppl., September 1940.
11. *Mathematical Theory of Heat Distribution During Welding and Cutting,* D. Rosenthal, The Welding Journal Res. Suppl., May 1941.
12. *Heat Flow in Arc Welding,* E. M. Mahla, M. C. Rowland. C. A. Shook and G. E. Doan, The Welding Journal Res. Suppl, October 1941.
13. *Gaseous Conductors—Theory and Engineering Applications,* James D. Cobine, McGraw-Hill Book Co., Inc., 1941.
14. *Temperature—Its Measurement and Control in Science and Industry,* L. R. Hodell, Reinhold Publishing Co., 1941.
15. *Effects of Cooling Rate on the Properties of Arc-Welded Joints in Carbon-Molybdenum 0.50 Plate,* W. F. Hess, The Welding Journal Res. Suppl., December 1942.
16. *Physics of the Arc and the Transfer of Metal in Arc Welding,* W. Spraragen and B. A. Lengyel, The Welding Journal Res. Suppl., January 1943.
17. *The Measurement of Cooling Rates Associated with Arc Welding and Their Application to the Selection of Optimum Welding Conditions,* W. F. Hess, L. L. Merrill, E. F. Nippes, Jr., and A. P. Bunk, The Welding Journal Res. Suppl., September 1943.
18. *Establishment of Cooling Curves of Welds by Means of Electrical Analogy,* V. Paschkis. The Welding Journal Res. Suppl., October 1943.
19. *Determination of Cooling Rates of Butt and Fillet Welds as a Result of Arc Welding with Various Types of Electrodes on Plain Carbon Steel,* W. F. Hess, L. L. Merrill, E. F. Nippes, Jr., and A. P. Bunk, The Welding Journal Res. Suppl., August 1944.
20. *Final Report on Residual Stresses in Ship Welding,* E. Paul DeGarmo and J. L. Meriam, OSRD Report No. 4867, March 1945.
21. *The Problem of Fracture,* J. H. Hollomon, American Welding Society, 1946.
22. *Residual Stresses in Intersecting Butt Welds,* E. Paul DeGramo, The Welding Journal Res. Suppl., August 1946.
23. *The Effect of Weld Length Upon the Residual Stresses of Unrestrained Butt Welds,* E. Paul DeGamo, J. L. Meriam and Finn Jonassen, The Welding Journal Res. Suppl., August 1946.
24. *Effect of Certain Block and Other Special Welding Procedures on Residual Welding Stresses,* Finn Jonassen, J. L. Meriam and E. Paul DeGarmo. The Welding Journal Res. Suppl., September 1946.
25. *Report on the Fracture of Metals,* Maxwell Gensamer, Edward Saibel and J. T. Ransom, American Welding Society, 1947.
26. *Some Tests of Large Welded Structures,* E. Paul DeGarmo, J. L. Meriam and R. C. Grassi, The Welding Journal Res. Suppl., May 1947.

CHAPTER 3

FUNDAMENTALS OF WELDING METALLURGY*

INTRODUCTION

METALLURGY OF welding is concerned with the properties of the metallic materials which are involved and the mechanical and thermal effects established during the welding process. In securing a satisfactory and homogeneous weld junction, temperatures are required ranging from well above the melting point to the ambient temperature of the sections being welded. This range of temperatures produces thermal changes including expansion and contraction, metallurgical effects such as grain growth and heat treatment, chemical reactions and changes in mechanical properties such as strength and ductility. The rate of heating and cooling incident to the making of any weld depends upon the particular process which is being used and the material and dimensions of the section being welded. Comparatively high rates of heating and cooling accompany a weld made by resistance welding, whereas comparatively slow rates of temperature change accompany a joint being made by gas welding. Extensive investigations have been carried out in order to establish the relationship of temperature and time for various welding techniques. For example, a weld bead deposited by the electric arc process upon a $^1/_2$-in. thick steel plate with a $^3/_{16}$-in. diameter electrode, using 175 amp., 26 volts and 6 in. per min. travel will show, in the base metal immediately adjacent to the weld metal, an increase from ambient to melting temperatures in approximately 7 seconds and a decrease from this maximum temperature to 572°F. (300°C.) in one minute. The effect of the welding process upon any material will be determined by the exact thermal cycle through which the material progresses. Expansion and metallurgical changes will be related to many of the common properties of the material which is being welded. The melting point of the weld metal or base metal will control the temperature at the fusion line. The specific heat and thermal conductivity will, for any given welding technique, determine the extent to which the base metal is heated. The contraction of the weld will, together with the expansion and contraction of the base metal in the zone adjacent to the weld, affect the stresses and distortion which may occur in the weld zone.

Most of the metals commercially used in weldments consist of one or two major elements with one or more alloying elements. For information regarding specific alloys, reference should be made to individual chapters discussing those alloys.

If a cross section of a weld is examined several zones will be evident. Usually two sections of plate material, together with a weld deposit, constitute the essential parts. The weld metal may assume a variety of shapes depending upon the type of joint. In some joints little or no molten metal is in evidence. Such a joint would be obtained by a welding process where pressure is used. In spot-welding, the joint comprises a nugget entirely surrounded by the base metal. In most of the arc and gas welding processes a portion of the base metal is melted and joined with the molten filler metal. In brazing no base metal is included in the molten weld metal. From a metallurgical standpoint, there must be considered the reactions of the weld

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* Prepared by a committee consisting of C. E. Jackson, Union Carbide & Carbon Research Labs., *Chairman;* I. T. Hook, American Brass Co.; G. O. Hoglund, Aluminum Company of America; T. E. Kihlgren, International Nickel Co.; G. G. Luther, Naval Research Lab.; W. E. McKenzie, U. S. Naval Gun Factory; R. D. Stout, Lehigh University.

metal in the liquid state, the mechanics of solidification, and the effects of thermal history in the solid state, as established by the welding process and by auxiliary heat-treating procedures. The base metal may contribute alloying elements, thus controlling the chemical composition of the weld metal. The heat evolved during welding must be dissipated throughout the weld joint, and much consideration has been given to the heat-affected zone immediately adjacent to the weld metal. In the further discussion of metallurgy of welding, it will be necessary to consider the effect of welding on metallurgical behavior of various materials. Much of the progress in the metallurgy of welding has resulted from the practical application of general metallurgical principles. Although the rates of heating and cooling and the maximum temperatures occurring at the fusion line are not identical to those encountered in heat-treating practices, many of the general principles of heat-treating are useful in interpreting the metallurgical effects of welding. The following section presents fundamentals of metallurgical behavior generally applicable to the metallurgy of welding.

EQUILIBRIUM AND NON-EQUILIBRIUM CONDITIONS

Principles of Alloy Diagrams

Alloy diagrams are charts which summarize the phase changes that take place in any of a series of alloy compositions as the temperature is changed. While certain features of these diagrams are known to obey the phase rule, the diagrams can only be constructed from experimental data. According to the number of constituents making up the alloy, it is designated as a binary, ternary or quaternary alloy, etc., having respectively, two, three or four, etc., components present. In order to understand the use of alloy diagrams, the reader may find it helpful to learn how such a diagram is obtained from laboratory experiments.

Let it be assumed that the alloys of copper and nickel are to be studied. A series of compositions of these metals is prepared and examined over a range of temperatures. For a beginning, the temperatures of melting and freezing are to be determined. One problem is to develop a technique to accurately determine these temperatures. Since melting and freezing involve absorption or evolution of heat, one of the best methods is to allow a molten bath to cool slowly while temperature and time measurements are made. The heat of solidification will cause a jog or discontinuity in the cooling curve, and thus the freezing temperature will be revealed. The shape of the jog will show the manner in which freezing takes place, as a pure metal always freezes at a single temperature, while alloys may freeze over a range of temperatures. The cooling curves of pure copper and of an alloy containing 50% copper with 50% nickel appear as shown in Fig. 1. At the points marked *A* and *B*, the jogs begin and end, respectively; these are the temperatures at which freezing begins and ends.

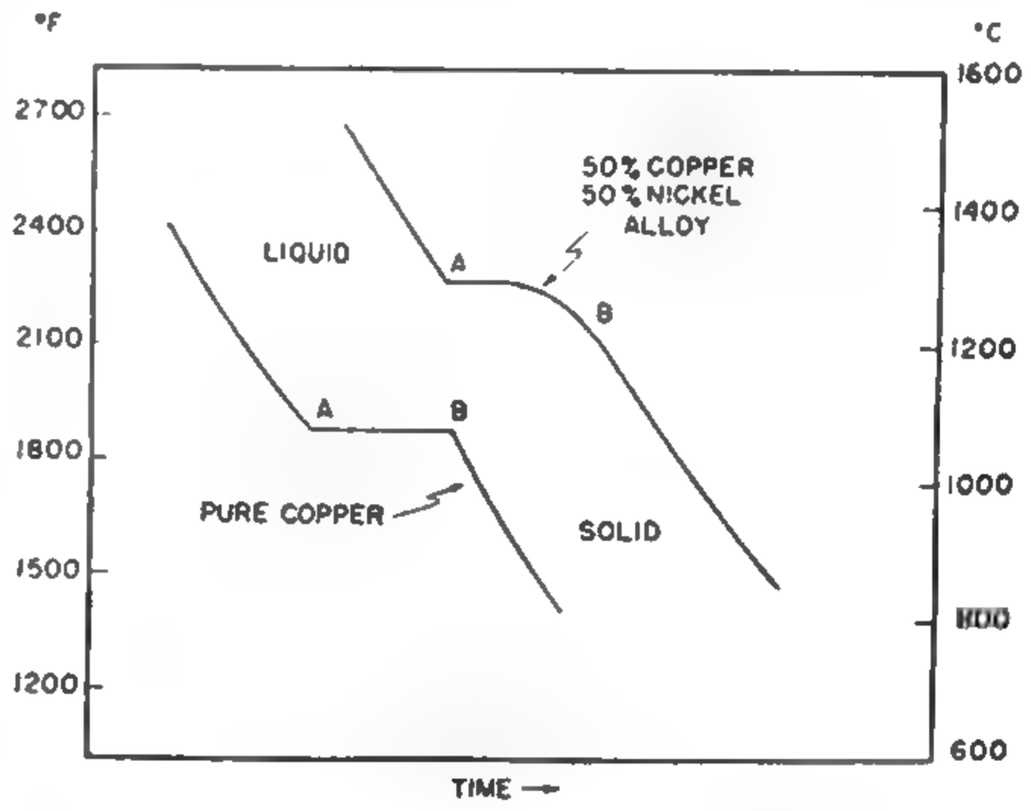


Fig. 1.—Typical Cooling Curves for Copper and a Copper-Nickel Alloy

If such information is obtained for a sufficient number of alloy compositions, the characteristics of a whole system will be determined. A single diagram can be used to plot the temperatures at which *A* and *B* occur for each alloy, as shown in Fig. 2. Temperatures are plotted on the vertical axis and alloy compositions on the horizontal axis. If all of the *A* points are connected by a line, called the *liquidus line,* the temperature at which any alloy in the system will start to freeze can be determined by erecting a perpendicular from the horizontal axis at a point corresponding to the composition of the alloy and reading the temperature at which it intersects the *A* line. If this particular alloy had been studied in the laboratory, its *A* point would have

been found to occur at this intersection temperature, but the diagram, when sufficiently established by data, will allow the start of freezing to be determined for all intermediate alloys without experiment.

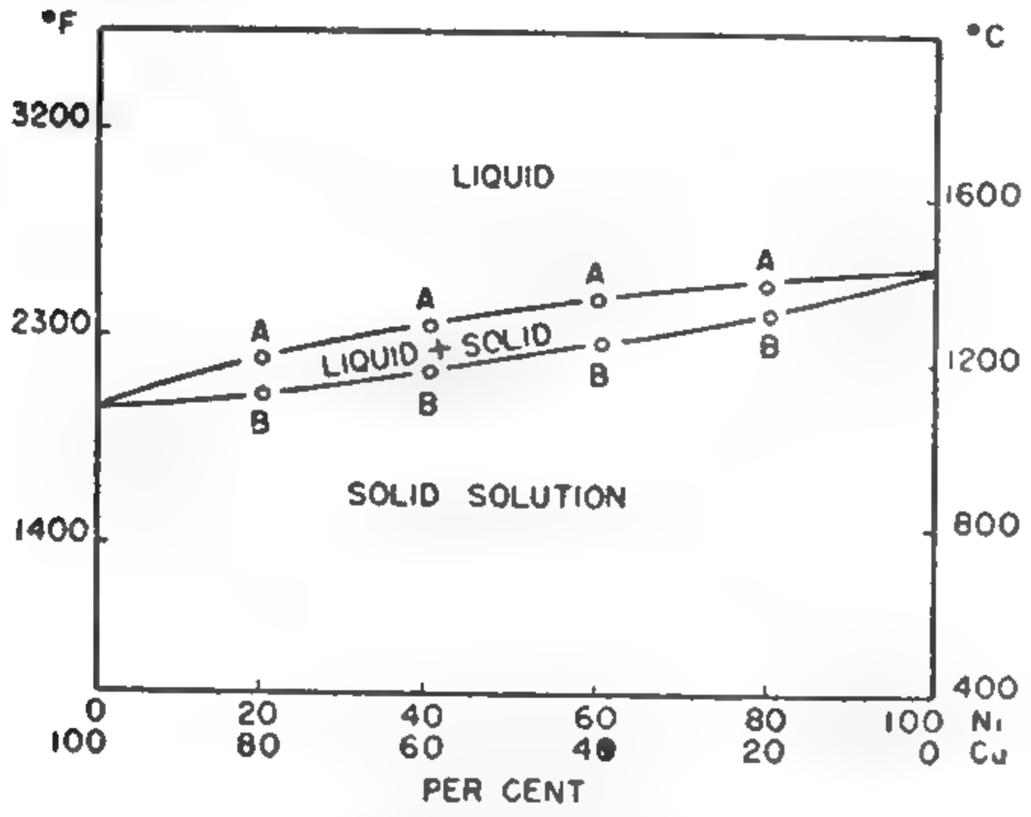


Fig. 2.—Copper-Nickel Equilibrium Diagram

Similarly, a line connecting the *B* points, called the *solidus line*, will show where freezing is complete. Thus, if any alloy is heated above the *A* line, or liquidus, it will be completely liquid; if it is at a temperature between the *A* and *B* line, it will be partially molten and partially solid; and at temperatures below the *B* line, it will be completely solid. The areas or *fields* on the diagram corresponding to these conditions of temperature and alloy composition can therefore be labeled *liquid, liquid and solid* and *solid.* Since copper and nickel mixed in any proportion form only one type of crystal structure in the solid state, they are said to form a *solid solution* alloy. Any other binary alloy system in which complete solid solubility exists will possess a similar form of diagram, differing only in the location and shape of the lines denoting the beginning and ending of freezing or melting.

It must be emphasized that the foregoing discussion is dependent upon the maintenance of equilibrium conditions, which require that any change occurring in an alloy is a reversible change. This means that any phase change due, say to a temperature drop, will be reversed by raising the temperature back to the initial point. Since the validity of alloy diagrams is contingent on equilibrium conditions, they are commonly called *equilibrium diagrams.*

Consideration will now be turned to another type of alloy diagram in which the component metals are not capable of dissolving into a single solid solution in all proportions. In this case, the metals will produce alloys in which there are two separate phases in the solid state. If cooling curves are conducted on a series of alloys between copper (Cu) and silver (Ag), the A and B points will assume the configuration shown in Fig. 3. One alloy in the series will be found to have a freezing point occurring at a single temperature, which will be the lowest of any composition. However, many alloys on either side of this composition will complete freezing at this same temperature. The lowest melting alloy is called a *eutectic,* and the diagram is called a eutectic diagram.

Some of the features of the eutectic diagram may be pointed out. If the portion of the diagram containing up to 9% Cu is examined, it will be noticed that freezing occurs in a manner exactly analogous to that in a solid solution system.

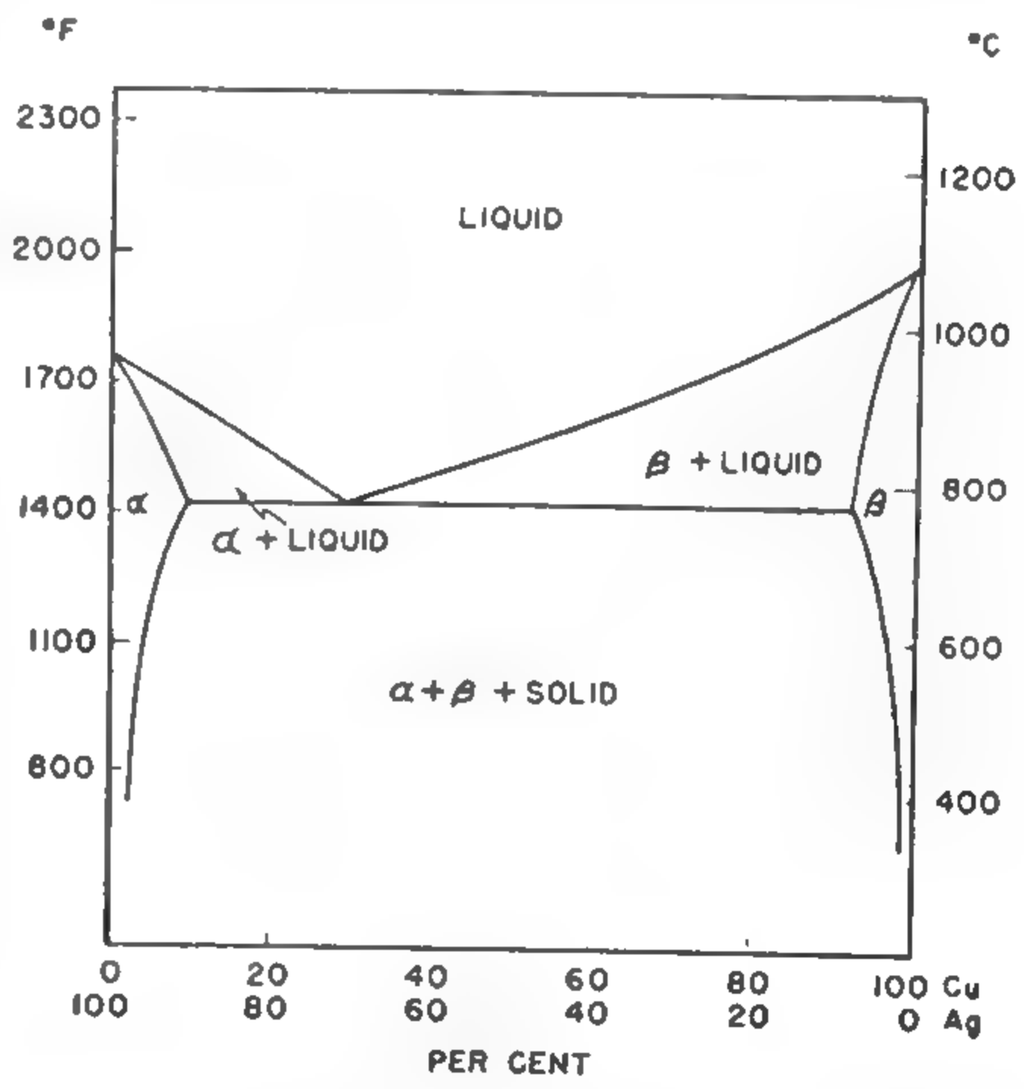


Fig. 3.—Copper-Silver Equilibrium Diagram

All solid alloys in this portion will be single-phase alloys containing crystals of the solid solution labeled "α." Likewise, all solid alloys between 92 and 100% Cu will be solid solution alloys containing only "β" phase. Thus, only the alloys lying between 9 and 92% Cu will form the eutectic type of structure.

The freezing of an alloy whose composition falls, say at 15% Cu, will be described. As the liquid alloy cools to its

A temperature, solid crystals will start to form. These will be crystals of α solid solution and are called primary crystals. This brings up an important point. The crystals which form cannot be of the same analysis as the liquid from which they originate. They must

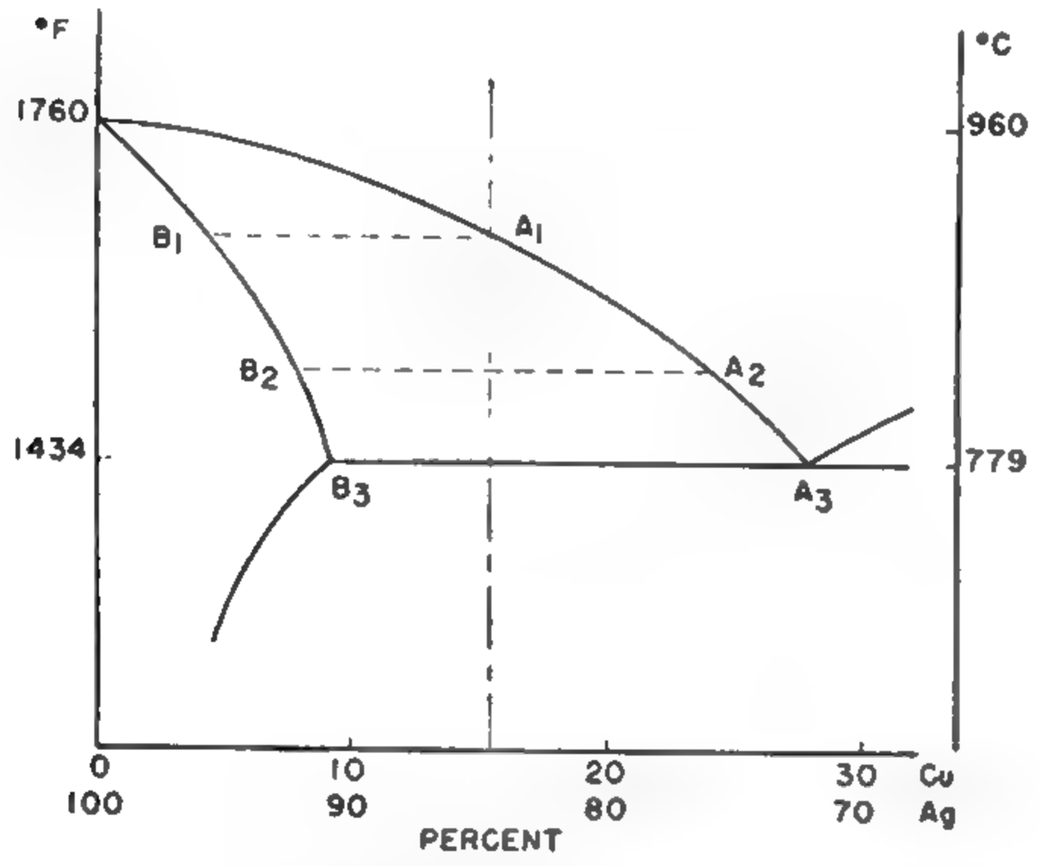


Fig. 4.—Changes in Composition During Solidification

be of such an analysis that they, taken by themselves since they are completely solid, constitute an alloy which is just completely solid at the temperature in question. The alloy filling this requirement uniquely is that located by the intersection of an isothermal line drawn from the A_1 point of the alloy over to the solidus at the point marked B_1 in Fig. 4. As freezing continues, the crystals which form will adjust their composition to continue to meet the condition that has been stated. Thus, at a lower temperature the α crystals will have the analysis indicated by point B_2, and by the time cooling has proceeded to the eutectic freezing temperature, they will have the composition shown by joint B_3.

Meanwhile, the liquid has been shifting in composition as well. Since the crystals forming are richer in silver than the original alloy, the liquid must be depleted in that metal. Its composition, by reasoning similar to that above, must be that of an alloy just completely molten at the stated temperature. Thus, when the crystals have assumed the composition shown by point B_2, the liquid will have the analysis indicated by the point A_2. At the eutectic temperature, the crystals will have the analysis shown by point B_3 and the liquid by point A_3, the eutectic alloy composition. At this temperature, the remainder of freezing must take place, and it will occur by the simultaneous freezing of α and β solid crystals. Because they form simultaneously, these crystals will be intimately mixed in a structure made of thin, alternate plates of the two phases or perhaps a salt and pepper type of intermingling. The final solid alloy, therefore, will contain the larger primary crystals of α formed at higher temperatures, together with the eutectic mixture of α and β. An alloy of eutectic composition will possess a solid structure composed entirely of the α and β mixture, while any alloy between the eutectic and 92% Cu will form primary crystals of β and a eutectic structure of α and β.

As might be expected there are many alloy systems in which the relations between the components are more complicated than those discussed above. However, these basic types have been described in some detail because the more complicated diagrams can almost all be subdivided into sectors which by themselves constitute either one or the other of these two types. Intermetallic compounds may form which are similar to chemical compounds in that there is a strong binding force between the atoms.

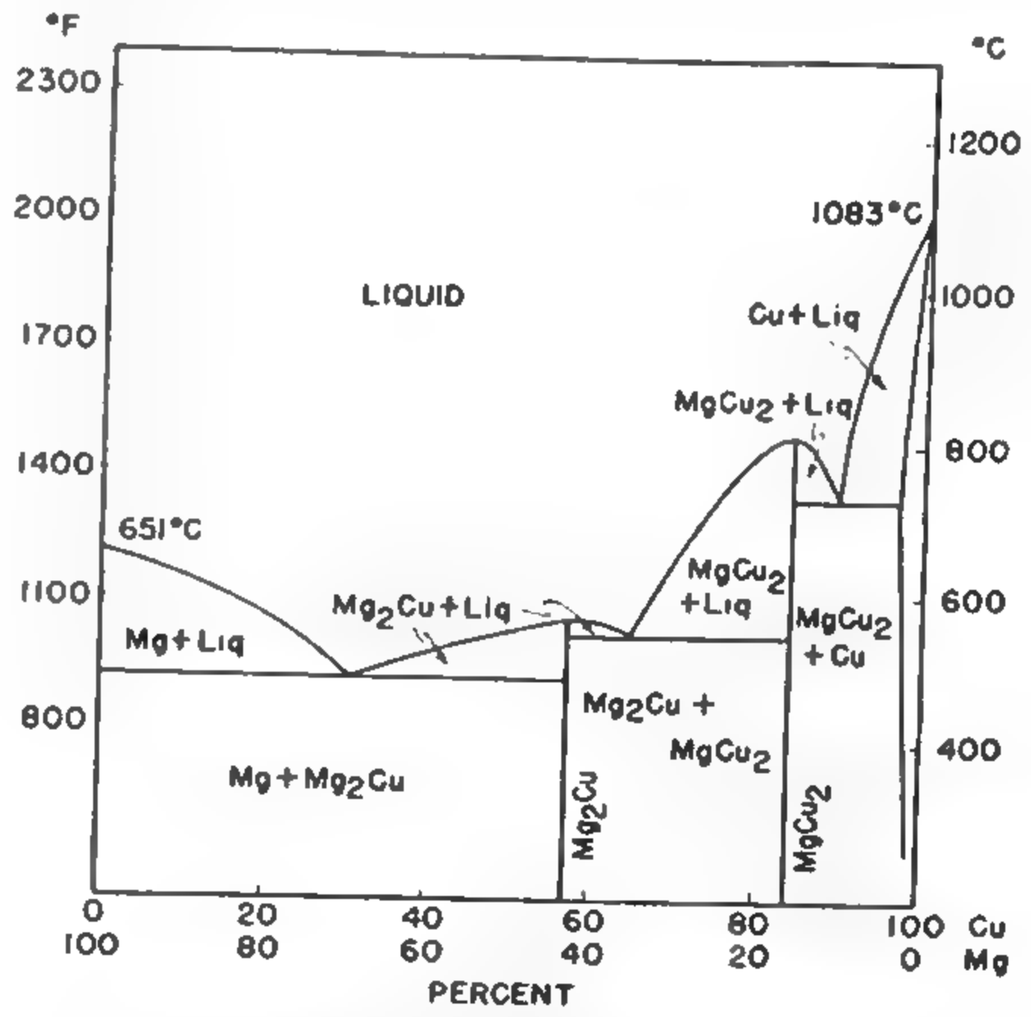


Fig. 5.—Magnesium-Copper Equilibrium Diagram

In an alloy system, an intermetallic compound is likely to behave much as if it were a single component. In an alloy binary system of magnesium and copper, two intermetallic compounds form: Mg_2Cu and $MgCu_2$. Each of these com-

pounds behaves as if it were a pure metal. The whole diagram shown in Fig. 5 could be reduced to three simpler diagrams by parting it at the compositions Mg_2Cu and $MgCu_2$.

As a further example of the construction of complex diagrams from simpler units, the iron-carbon diagram will now be described, since it is perhaps the most important single alloy diagram in metallurgy.

more complex relations than those shown by Cu–Ni or Cu–Ag alloys. It is possible, however, to divide the alloy diagram into simpler segments, as was demonstrated above. In the upper left-hand area of Fig. 6, the diagram is typical of any solid-solution alloy series, except for a further complexity at low carbon contents which may be ignored here because it has no importance in ordinary iron-carbon alloys. The range

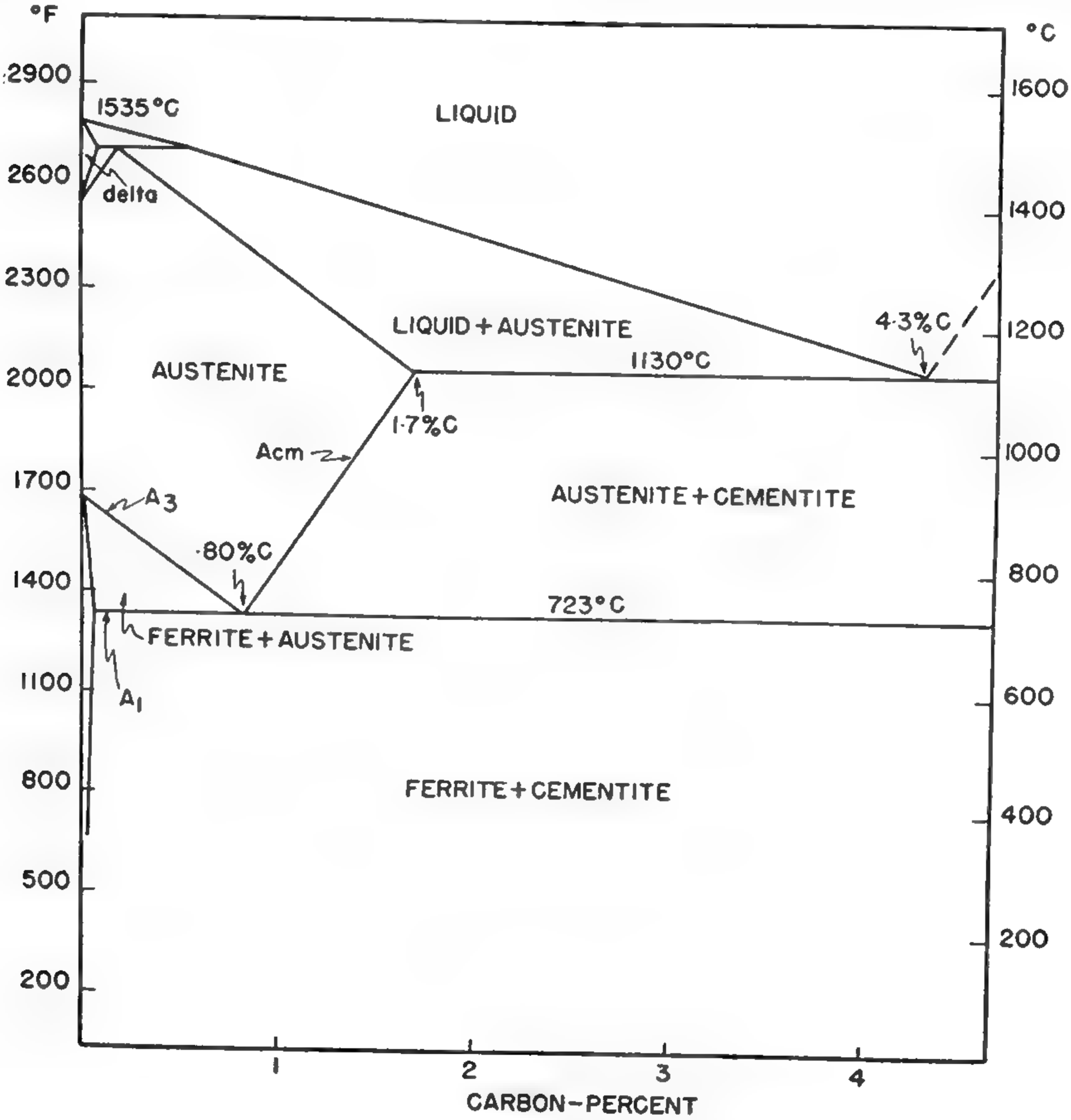


Fig. 6.—The Iron-Carbon Equilibrium Diagram

The Iron-Carbon Diagram.—It is important that some consideration be given to the iron-carbon equilibrium diagram, from which a better understanding of the behavior of steel can be gained, especially in connection with welding thermal cycles and with heat treatment.

The alloys of iron and carbon display of composition included, 0 to 1.7% C, is usually regarded as the limit of steel compositions. Thus, all steels freeze as solid solution alloys. The solid solution formed has been named *austenite*. The upper right area is similar in appearance to the eutectic type of diagram. The Fe–C alloys above 1.7% C compose the cast

irons and all solidify with a eutectic present in their structure. Since few cast irons exceed 4% carbon, they usually commence freezing by the formation of primary crystals of austenite, as the diagram shows.

The lower left portion of the diagram is of special significance to the unique properties of steel and departs, at least in one respect, from the basic diagrams covered previously. One might guess that another eutectic is depicted in this lower area if it were not for the fact that all of the alloys are already completely solidified before they cool to this temperature range. Therefore, it must be that a eutectic-like structure forms from a solid instead of a liquid solution. In this case, austenite decomposes to form two new phases: one is almost pure iron and is called *ferrite;* the other is a compound of iron and carbon, Fe_3C, which is called *cementite.* As will be seen later, it is this portion of the diagram which helps to explain some of the effects that are produced in steel by the thermal cycle of welding.

Solidification of Metals

Solidification of alloys, such as steel, does not occur at a fixed temperature, but within a range. Initiation of solidification begins at the liquidus and is complete at the solidus temperature (Fig. 6). The mixture of solid and liquid states extends over what is called the *mushy stage.* The first crystals which freeze will tend to be richer in the higher melting constituent in obedience to the principles of the alloy diagram discussed previously and illustrated by Fig. 4. As freezing proceeds, the crystals will become richer in the lower melting constituents and thus produce a heterogeneity of composition in the final solid metal. It is this mechanism of freezing that gives rise to segregation in cast alloys. By exposure to high temperatures for a long period of time or by extensive plastic working of the metal, the composition can be equalized or homogenized considerably. Besides the reduction of segregation, working of the metal will tend to introduce refinement in grain size.

The physical properties of a solid metal or alloy are influenced by the maximum temperature of superheat of its liquid phase and the rate and mechanism of its solidification. Characteristics inherited from these temperatures are only partly removed by extensive mechanical and thermal treatment of the solid metal. The differences between weld metal and forged and cast metal structures are in part attributable to the high temperatures attained during fusion in welding and the rapid solidification rate which follows.

Dendritic Solidification.—Solidification of a molten metal does not usually initiate simultaneously throughout its mass, but begins at points called *nuclei* in the cooler regions of the metal and proceeds in a direction opposite to the thermal cooling gradient. The solidification advances in all directions which are normal to its main axis of progression, so that a dendritic or tree-like pattern is formed. The secondary, tertiary and succeeding minor axes, all normal to their preceding members, fill out the spaces between adjacent dendrites until all the mass is solid. The dendritic growth of a crystal is shown in Fig. 7.

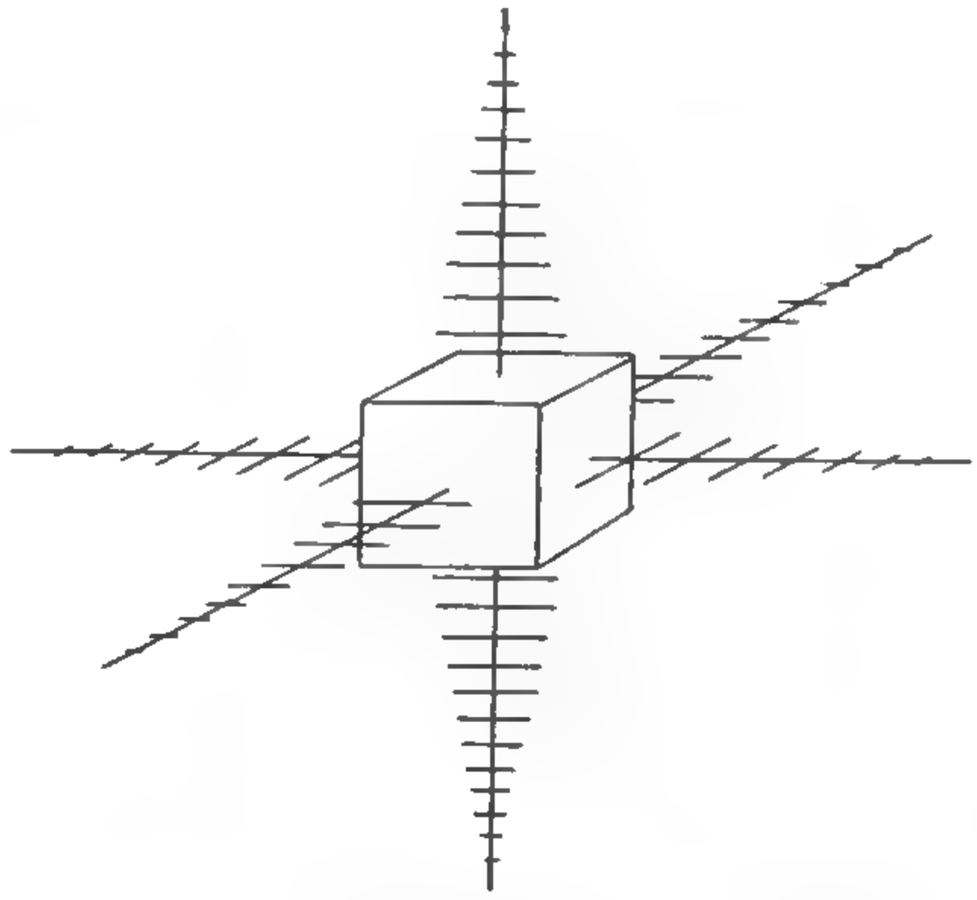


Fig. 7.—Dendritic Growth of Crystal

Grain formations which built up the dendrite may be subject to growth by recrystallization if two or more crystallites are nearly alike in orientation. Under favorable circumstances, one assumes the same atomic arrangement as the other and becomes a part of it. Too rapid cooling lowers the atomic mobilities which permit this crystal growth; high temperatures favor this action. The grain formation from individual nuclei is shown in Fig. 8.

Weld Metal Solidification.—If molten metal solidifies upon a chilling surface, such as a mold or the base metal in a

welding operation, there is formed immediately near this surface a thin, solid layer of practically the same composition as the liquid metal. The rapidity of solidification prevents any great selective solidification with varying composition. At the same time, the original filler metal composition, in the case of added weld metal, is modified by mixture with base metal, which is fused by the heat of welding. The extent or penetration of this fusion and incorporation of either base metal or sublayer of added weld metal is a function of the electrode or welding process used, the current, rate of travel or time cycle, and all the factors concerned with transfer of heat away from the welding zone.

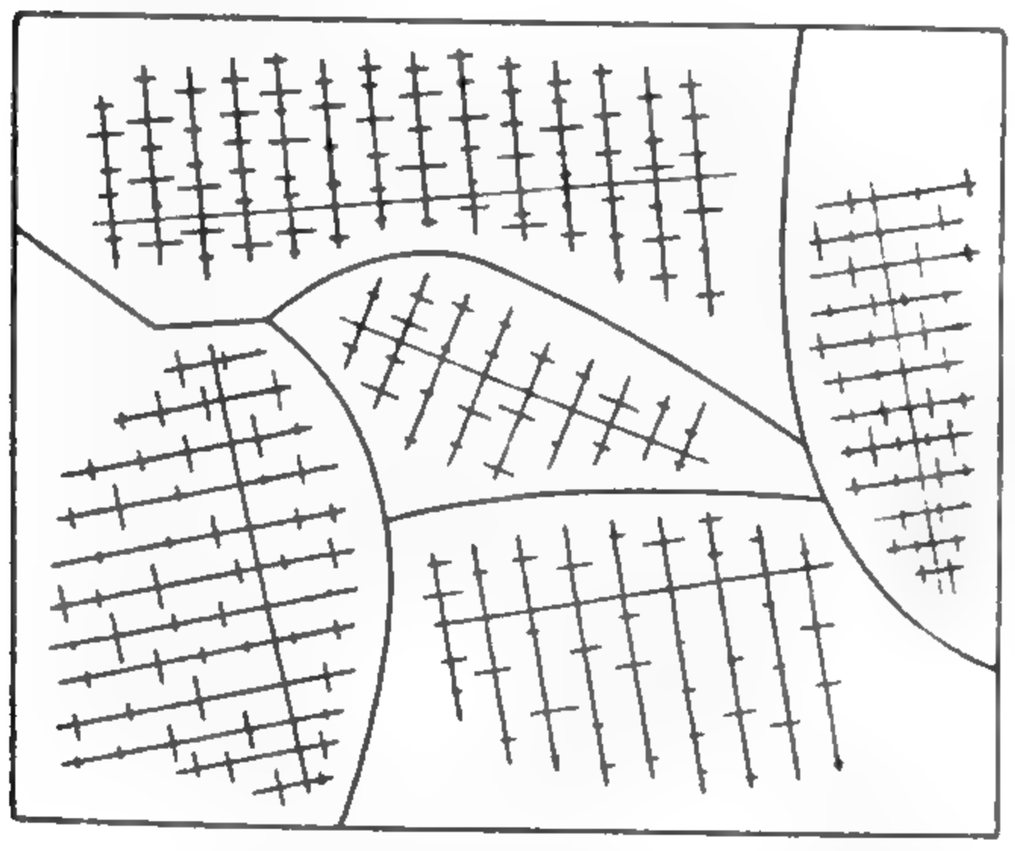


Fig. 8.—Grain Formation from Individual Nuclei

The heat effect, measurable by the amount of fusion, penetration and alloying, is important with respect to reaction of the liquid metal with the base metal. It is observable in respect to effect on undercutting in the side walls of weld grooves, metal shrinkage, gas formation and distortion in the assembled structure. Undercutting or the melting away of the side walls of the base metal is a frequent cause of slag entrapment in the undercut cavity.

In many welding processes the extreme rapidity of freezing of the added weld metal may approach the condition mentioned above where little preferential solidification can occur and the final composition is practically uniform. Heavier weld deposits with higher heat input permit more pronounced dendritic solidification. The primary axes of these dendrites are relatively low in impurities, while the interstices of the dendrites are most concentrated in them. However, after the solidification, some equalization of composition may occur by slow migration or diffusion of the elements.

Atomic Ordering and Crystallization.—The solidification of a metal is attended by a systematic arrangement of atoms from a disordered or random distribution in the liquid state into one of orderly spacing in their solid state. A single system of orderly arrangement does not extend throughout the metal mass, but initiates from a number of sources called nuclei wherever a small aggregation of atoms can assemble into order and continue to grow. These nuclei develop into a crystal, which is an aggregation with a definite internal structure or arrangement of atoms throughout and forming a coherent part of the whole.

It is to be noted that pure iron, which exists in several different forms depending upon temperature, undergoes three allotropic transformations in cooling from the solidus to room temperature (see Fig. 6). At the A_4 temperature of 2535°F. (1390°C.), the delta ferrite, first to solidify, is transformed to gamma iron or austenite. At 1670°F. (910°C.) the gamma or austenitic phase changes to alpha ferrite. Both the delta and alpha phases crystallize with a body-centered cubic lattice. This crystallization results in an atomic packing with a representative unit cell having atoms at all corners of the cube and one at the cell center. The gamma phase has a face-centered lattice arrangement with atoms at all corners of a cubic cell and in the center of all six faces. The crystal or grain consists of a parallel assembly of such cells in contiguous relationship. (See Figs. 9 and 10.)

A perfectly formed crystal is bounded by a series of plane surfaces characteristic of its chemical composition. This external appearance is indicative of the internal geometry of atomic lattices. Few industrial alloys, however, permit the formation of perfect crystals, since their growth is interrupted by adjacent crystals developing from nearby nuclei. The incomplete and necessarily irregular crystals are known as grains. They are strongly bonded together by the intergranular matter of randomly oriented atoms. The high strength of this intergranular material, together with the differences in

orientation among the constituent grains, results in a yield strength which appreciably exceeds that of a single crystal.

The addition of carbon to iron results in a proportional shifting of these allotropic temperatures and lowering of the liquidus and solidus ranges. It likewise changes the composition of austenite and permits the formation of iron carbide or *cementite*. In the iron-carbon constitutional diagram, shown in Fig. 6, practically complete equilibrium conditions are assumed in which sufficient time is given for essential completion of all reactions. The constitutional diagram does not indicate the transition products or the factor of time in heating or cooling. The effects of these factors will be discussed later.

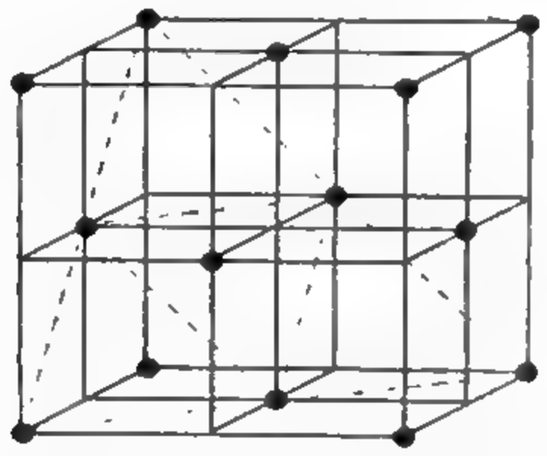


Fig. 9.—Face-Centered Cubic Lattice Typical of Austenite

In low-carbon steels the delta phase with a body-centered cubic lattice is first to solidify but is converted to the gamma phase with a face-centered cubic lattice at only slightly lower temperatures. At higher carbon contents, the gamma iron forms directly from the liquid phase. The gamma constituent is a solid solution of carbon or iron carbide in gamma iron, and at lower temperatures it precipitates the carbon either as pearlite or in the free condition. Below some 0.83% carbon, ferrite is precipitated from solid solution before the cementite is rejected, and the temperatures at which this begins are indicated in the A_s line. Since ferrite has very little solubility for carbon, the concentration of this element is increased in the remaining untransformed austenite. When this concentration reaches 0.83%, which is the eutectoid composition, there is a simultaneous precipitation of ferrite and carbide below 1333°F. (723°C.) in a characteristic and intimate arrangement known as *pearlite*.

If the eutectoid composition of 0.83% carbon is exceeded, iron carbide is the first phase to precipitate from austenite starting at the A_{cm} line in Fig. 6. At the lower limit of its solubility at the A_1 temperature, the remaining austenite is converted to pearlite. The eutectic of austenite and cementite, which is characteristic of cast iron, is formed from compositions of higher carbon contents. At lower temperatures, the final constituents are cementite, pearlite and ferrite, and in the presence of high silicon and slow cooling rates, the cementite may decompose to graphite. In all of these alloys ferrite has a small but measurable solubility for carbon; a maximum of only 0.03% at room temperature.

Transformations in Steel

Recrystallization.—The transformations in steel not only cause a rearrangement of the atomic pattern, but are accompanied by recrystallization, since the transformation from the old phase or phases, to the new, initiates simultaneously from a large number of nuclei and proceeds until interrupted by adjacent recrystallized grains. Grain refinement is ordinarily accomplished in industrial practices by heating steel to just above the A_3 temperatures, which assures that all of the previous structure is transformed and recrystallized. If the temperature is carried much above the A_3 limit and well into the completely austenitic region, the grain size increases by growth in which two or more adjacent grains assume the same crystal orientation and unite as one.

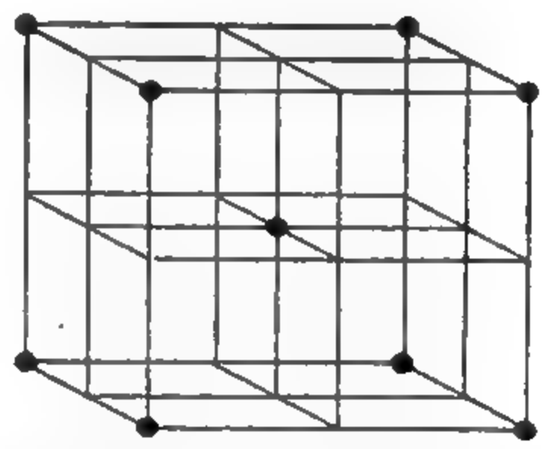


Fig. 10—Body-Centered Cubic Lattice Typical of Ferrite

Growth differs from recrystallization in that it is independent of phase transformation, since the same type of atomic arrangement is maintained. It implies an effect similar to a crystal rotation so that grains of the same lattice spacings also assume the same crystallographic axes as adjoining grains and thus merge to become larger grains.

In plain carbon steel welds of low-

carbon content, we rarely find austenite at room temperature in either the added or base metals, since this phase transforms rapidly during cooling and is retained only by exceedingly drastic quenching. Although this is true, austenite may transform to a variety of products, depending upon its aggregation, which is controlled by cooling rate. Since the constitutional diagram shows only the stable equilibrium association of phases, it cannot predict the products of the various thermal treatments which govern the solid state reactions in weld metal or in the base material affected by the welding heat where equilibrium seldom exists.

The results of grain refinement by recrystallization and those of grain growth at elevated temperatures are nicely illustrated in the welding process. For example, the moderately coarse as-welded structures of weld deposits can be refined by a superimposed layer of weld metal which carries the temperature of the underlying bead just above the upper critical temperature or A_3. The chilling action of the thermally conductive base metal prevents excessive temperatures and grain growth. However, in some weld zones the temperatures may reach values well above the A_3 limit, and grain growth results therefrom.

Low-carbon steel base metals are generally of higher carbon content than the added weld metal, and, therefore, their recrystallization occurs at somewhat lower A_3 temperatures. Frequently the microstructure of the heat-affected areas in a single weldment shows both an area of grain refinement and one of very evident growth. The thermal histories which are revealed by these structural modifications are reflections of the heat effect of the welding technique and the heat balance as affected by the physical dimensions of the structure.

Solid Solubility.—Among the elements common to steel, silicon and phosphorus are most soluble in alpha or delta ferrite and further its formation, while carbon, manganese and nitrogen have a higher solubility in austenite or gamma iron and extend the temperature range in which it can exist. The solubility differences of elements in the two phases are evident in commercial steels, by segregation and precipitation from solid solution. Of the elements mentioned, carbon is by far the most responsive to solubility differences. Manganese and silicon are usually not present in amounts which even approach their maximum solubility in the alpha or gamma phase. The usually restricted amounts of nitrogen and oxygen minimize the importance of their changes in solid solubility. Nevertheless, in low-carbon weld metals the contribution of the last two elements to the mechanical properties may be more evident, as the carbon is less effective.

Precipitation from Solid Solution.—Precipitation of carbon as iron carbide from austenite can be modified to give an extensive diversity of final structures. This may be accomplished by drastic quenching to preserve the austenitic or martensitic state, then tempering or regulating the austenite decomposition under isothermal time-temperature conditions. A less definite, but frequently the only expedient, method of attaining the desired constituent products is to control the rate of cooling from the austenite range or the A_3 temperature. The addition of alloy elements also influences the stability of the austenite and may lower its rate of transformation and, if this is not too sluggish, increases the ease with which the transformation reactions can be consistently controlled. Since the kinetics of the transformation process is so important and involved, a separate section will be given to its consideration.

The precipitation of elements of low concentration in steel such as nitrogen and oxygen does not show an abrupt solubility change at the phase transformation temperatures. Both of these elements, and carbon as well, show a minor solubility in alpha iron. This solubility decreases with only a moderate gradient as the temperature drops below the A_1. The relatively slow diffusion and coalescing rate at these lower temperatures and the small concentrations involved result in a slow precipitation of wide scattering and often of submicroscopic size. By raising the temperature and increasing the time period, a coalescence of the precipitated phase may be obtained to the point that microscopic identification is possible.

Austenite Transformation in Plain Carbon Steel.—The transformation products from the decomposition of austenite in plain carbon steel can vary widely in microstructure and in the mechanical properties that they confer on the steel

in accordance with the time rate of cooling from above the A_3 temperature and the dwell at any specific temperature. Rapid and drastic quenching procedures result in the formation of a hard, brittle microstructure known as martensite, and the tendency toward its formation increases strikingly with carbon content. It is to be noted that, in general, the greater the carbon content the greater the martensitic hardness which can be obtained after a drastic quench. The maximum hardness after a drastic quench depends upon the carbon content alone, as shown in Fig. 11. Alloying additions do not increase the maximum hardness. This behavior emphasizes the role of lower carbon in the composition of steels for welding.

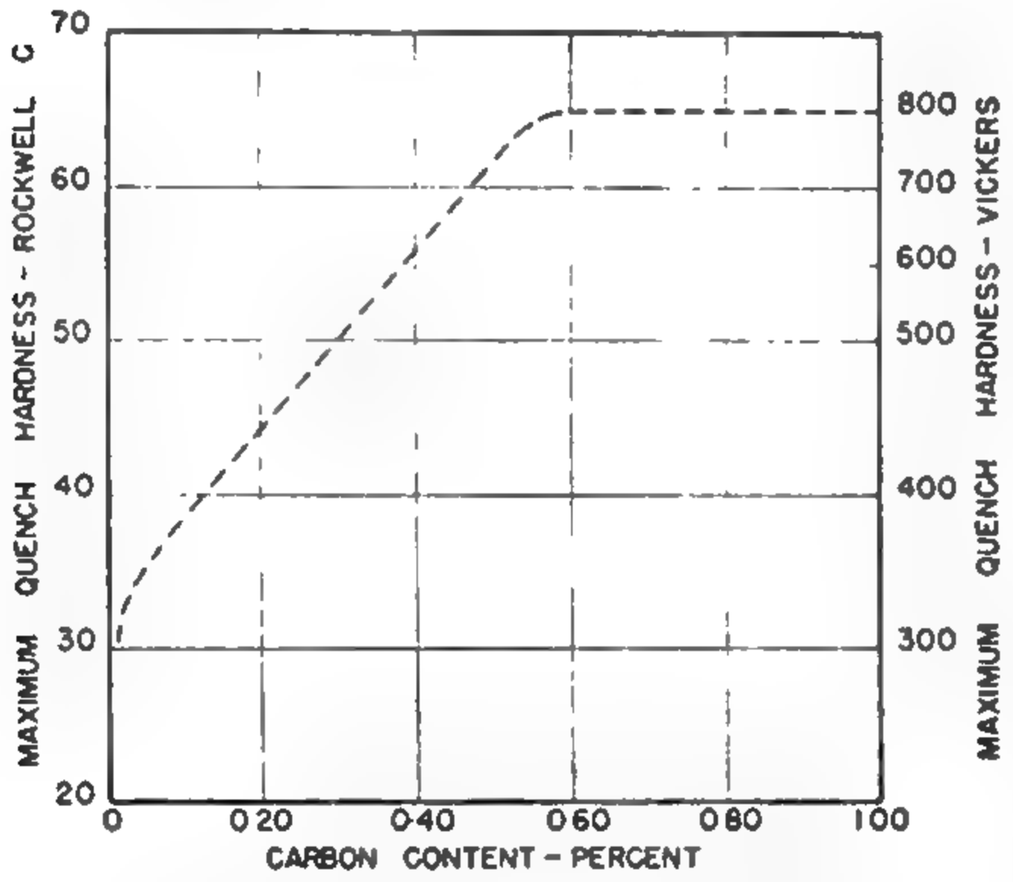


Fig. 11.—Influence of Carbon Content on Maximum Quench Hardness

For most practical purposes, the austenitic decomposition products of interest in industrial practices are martensite, pearlite, ferrite and cementite. Martensite is generally accepted as a transitional product from the gamma-alpha transformation. It has a tetragonal lattice and can be represented by a strained alpha ferrite supersaturated with carbide of ultramicroscopic fineness. Its microstructural appearance is *acicular* or needle-like on the etched surface of polished specimens. (See Fig. 12.) It is hard and brittle to a degree dependent on the carbon content.

On cooling from above the A_3 temperature at progressively lower cooling rates, a limiting critical rate for martensite formation is reached, beyond which slower cooling permits the formation of pearlite in its stead. The pearlite structure develops from a simultaneous precipitation of cementite, Fe_3C, and ferrite in a lamellar and parallel array. The coarseness or the width of the carbide and ferrite lamellae increases with slower cooling rates. At more rapid rates, the separate constituents of this association are microscopically resolvable only under high magnification, so intimate is their assembly.

Pearlite is a characteristic constituent in most non-austenitic base metals employed in welding. At high magnifications the appearance of the etched surface of polished specimens containing pearlite is that shown in Fig. 13. A pearlitic steel containing 0.83% carbon will be made up entirely of pearlite. Lower carbon pearlitic steels will contain ferritic and pearlitic areas with a distribution depending upon the carbon content. (See Fig. 14.) Low-carbon weld metals, however, contain a ferrite-carbide aggregate of related but dissimilar assembly suggesting local regions of finely spheroidized cementite but still in close aggregation (Fig. 15).

Method of Heat Treatment.—Slow cooling from above the upper critical or A_3 temperature is known as full annealing. This usually gives the ductile properties characteristic of the presence of coarser pearlitic aggregates. A release of internal stresses from mechanical treatment or differential thermal expansion also accompanies annealing, since the thermal energy and necessary time for plastic readjustment of these stresses are afforded by this treatment. Normalizing or cooling in still air from above the upper critical or A_3 temperature results in finer structures and improved toughness over those obtained by annealing.

If rapid quenching to room temperature or normalizing is followed by a supplementary heat treatment under the lower critical or A_1 temperature, modification of the martensite or quench structures can be accomplished. A heat treatment consisting of reheating to just below the A_1 temperature, holding for a period of time, followed by slow cooling to room temperature is known as *process* annealing or stress-relief annealing. This results in a microstructure in which the carbides tend to assume globular form within the ferritic matrix. If the holding is appreciably prolonged, the carbide particles coalesce

Fig. 12.—Typical Acicular Microstructure of Martensite

1000 ×

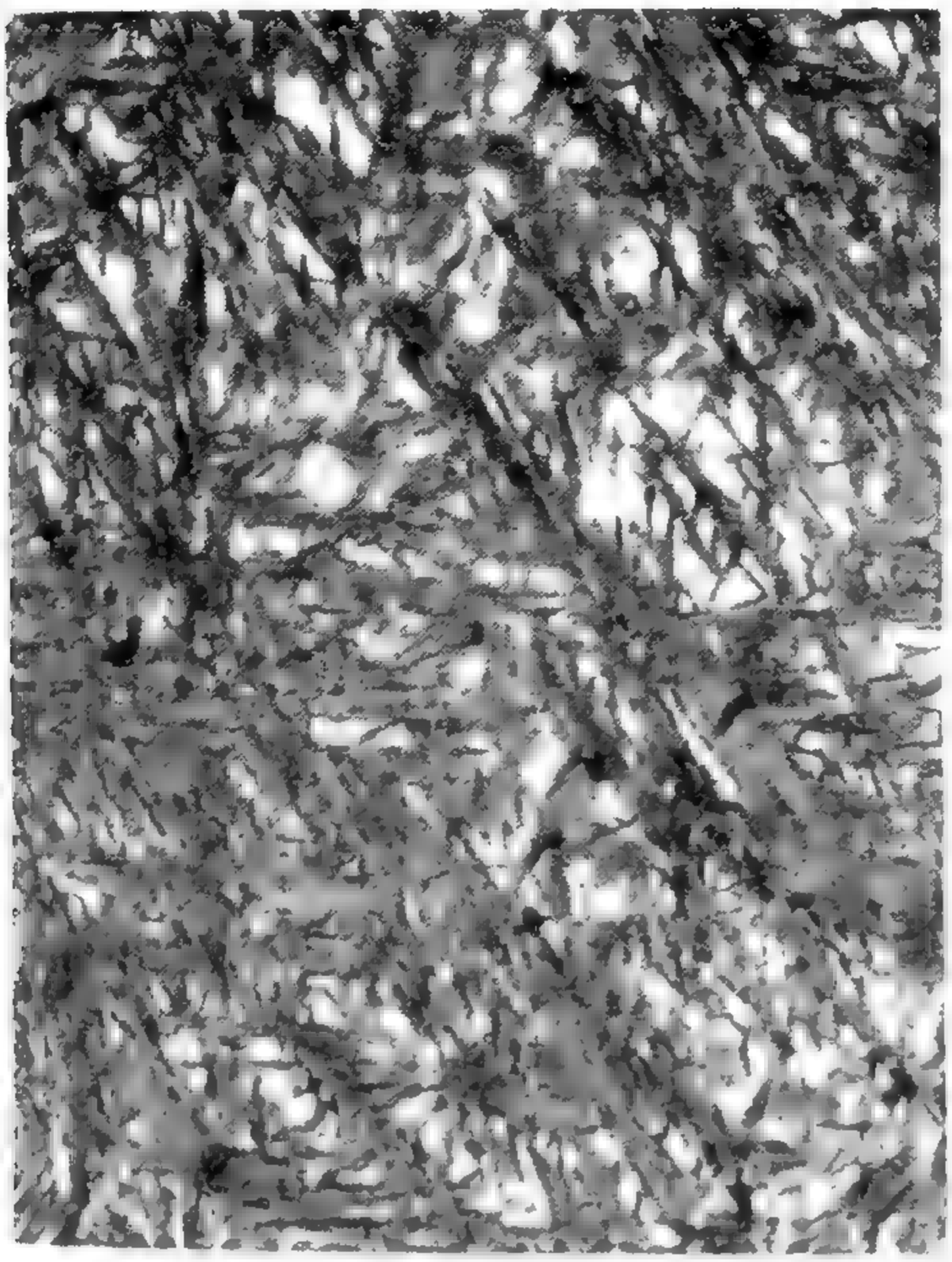


Fig. 13.—Typical Lamellar Microstructure of Pearlite

1500 ×

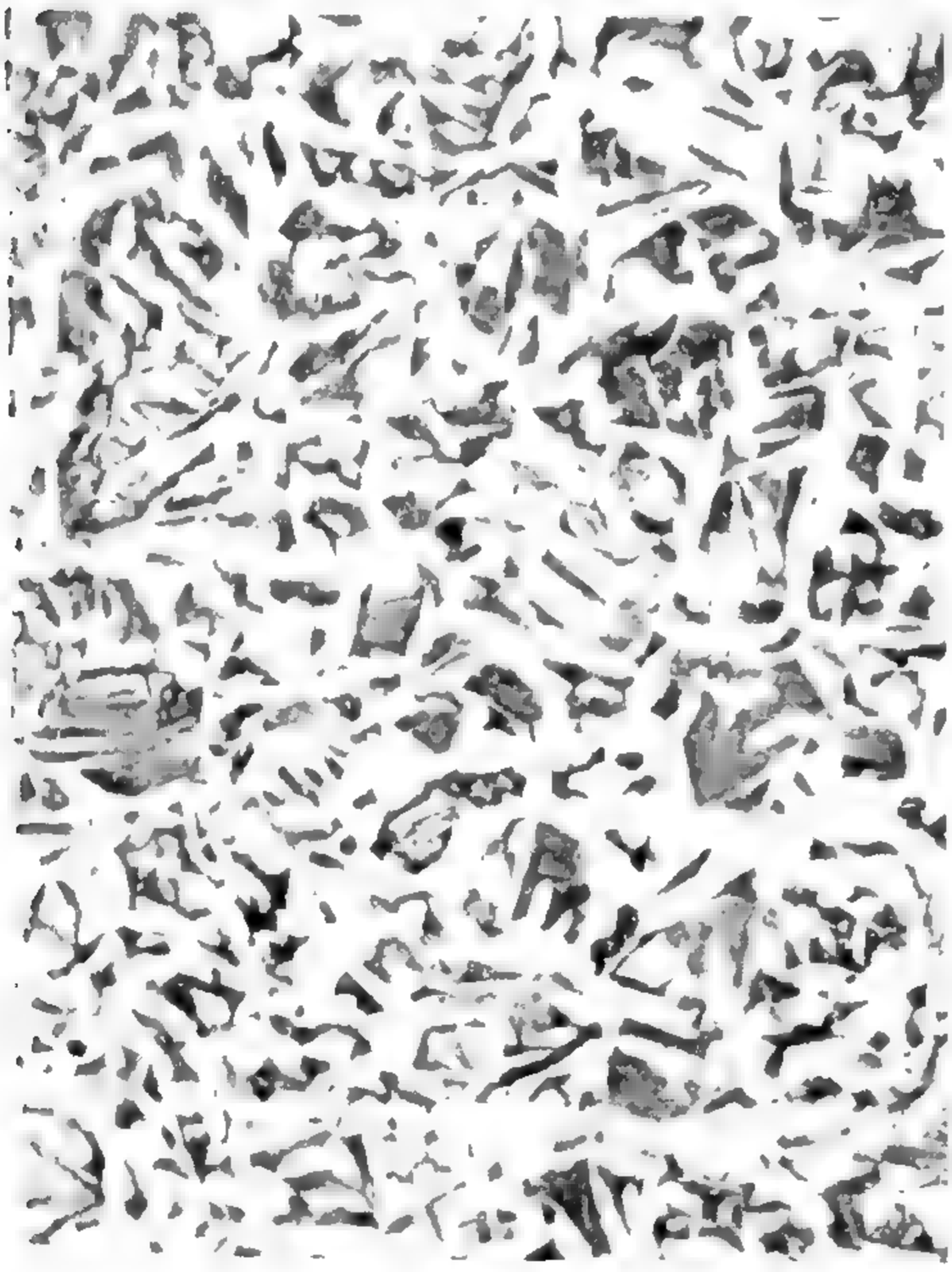


Fig. 14.—Typical Microstructure of Low-Carbon Pearlitic Steel Containing Areas of Pearlite (Dark) and Ferrite

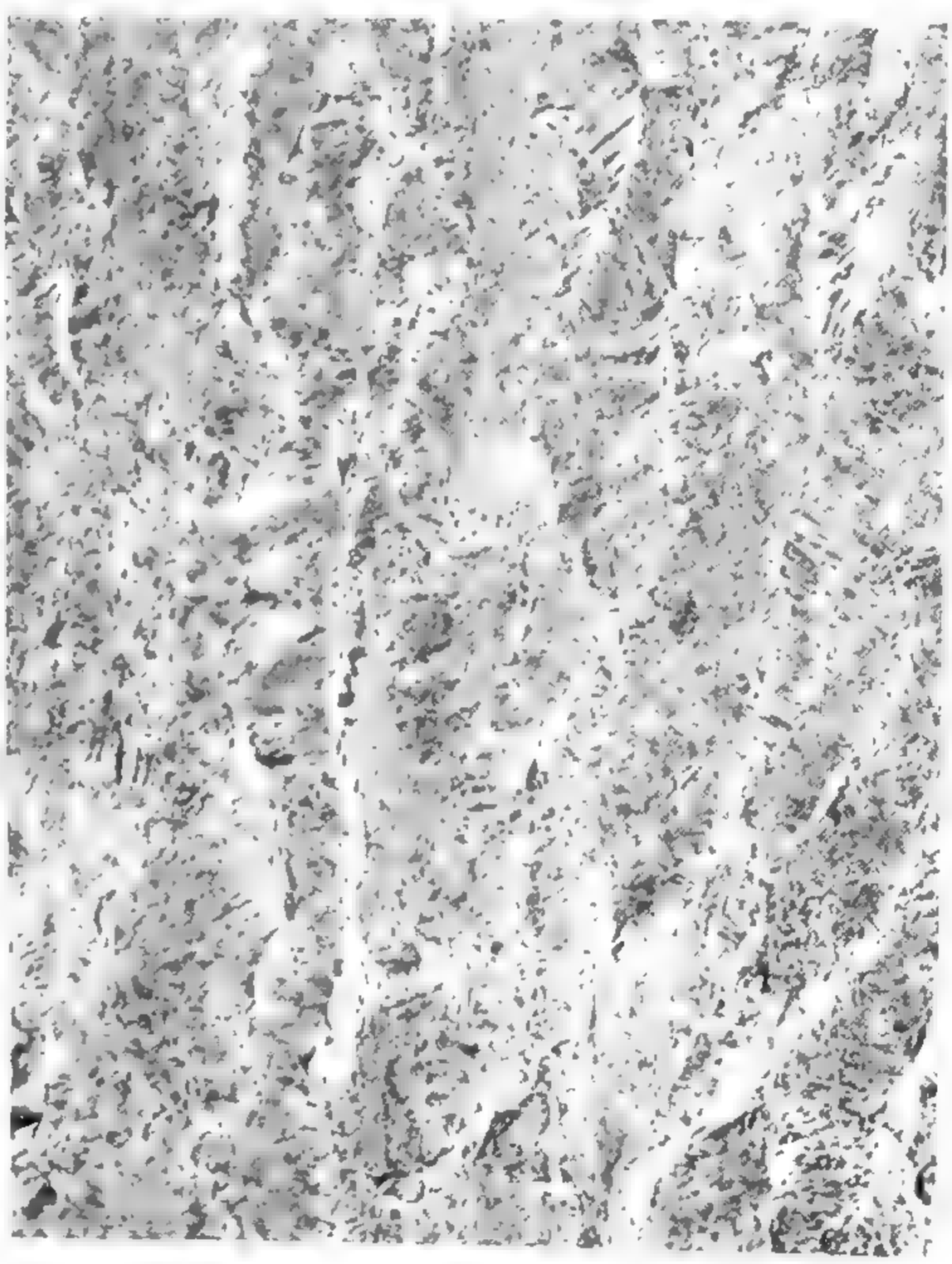


Fig. 15.—Typical Microstructure of Low-Carbon Steel Weld Metal

100 ×

into larger globules. This longer treatment imparts the maximum softness to the structure and is known as *spheroidization.*

A reheating of quenched steels at temperatures under the A_1 limit is known as *tempering.* The higher tempering temperatures permit nearly complete dissociation of the carbide and ferrite phase, while the lower temperatures produce more compact and nodular aggregations. stresses. Cooling from tempering temperatures may be conducted in air or other coolants.

Isothermal Transformation

The importance of the transformation rate of steel at any given (isothermal) temperature is that it provides a useful measure of relative rates of cooling or prolonging of postheat treatment required to prevent embrittlement.

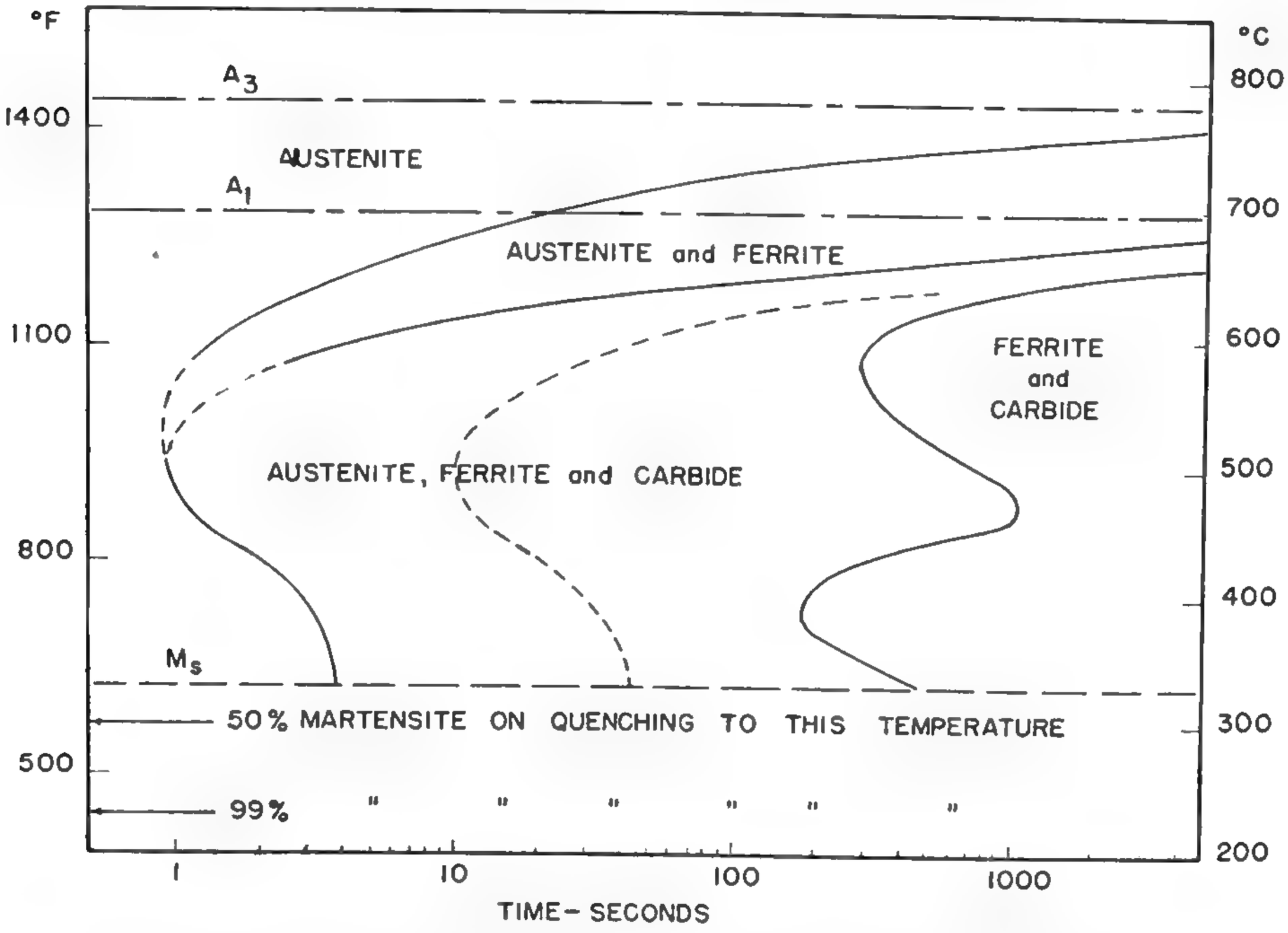


Fig. 16.—Isothermal Transformation Diagram of a 0.35% C, 1.85% Mn Steel

While all of these modification products from martensite are essentially aggregates of ferrite and cementite, there is an appreciable difference in their microscopic appearance. At relatively low tempering temperatures of about 400°F. (204°C.), martensite prevails practically unmodified, and if any residual austenite should be retained from quenching, it is transformed to martensite by this treatment.

To some extent, a longer time period of tempering at lower temperatures may correspond in effect to shorter periods at higher temperatures. However, the relationship is not strict. Both increased temperature and time of holding in this treatment help to eliminate internal

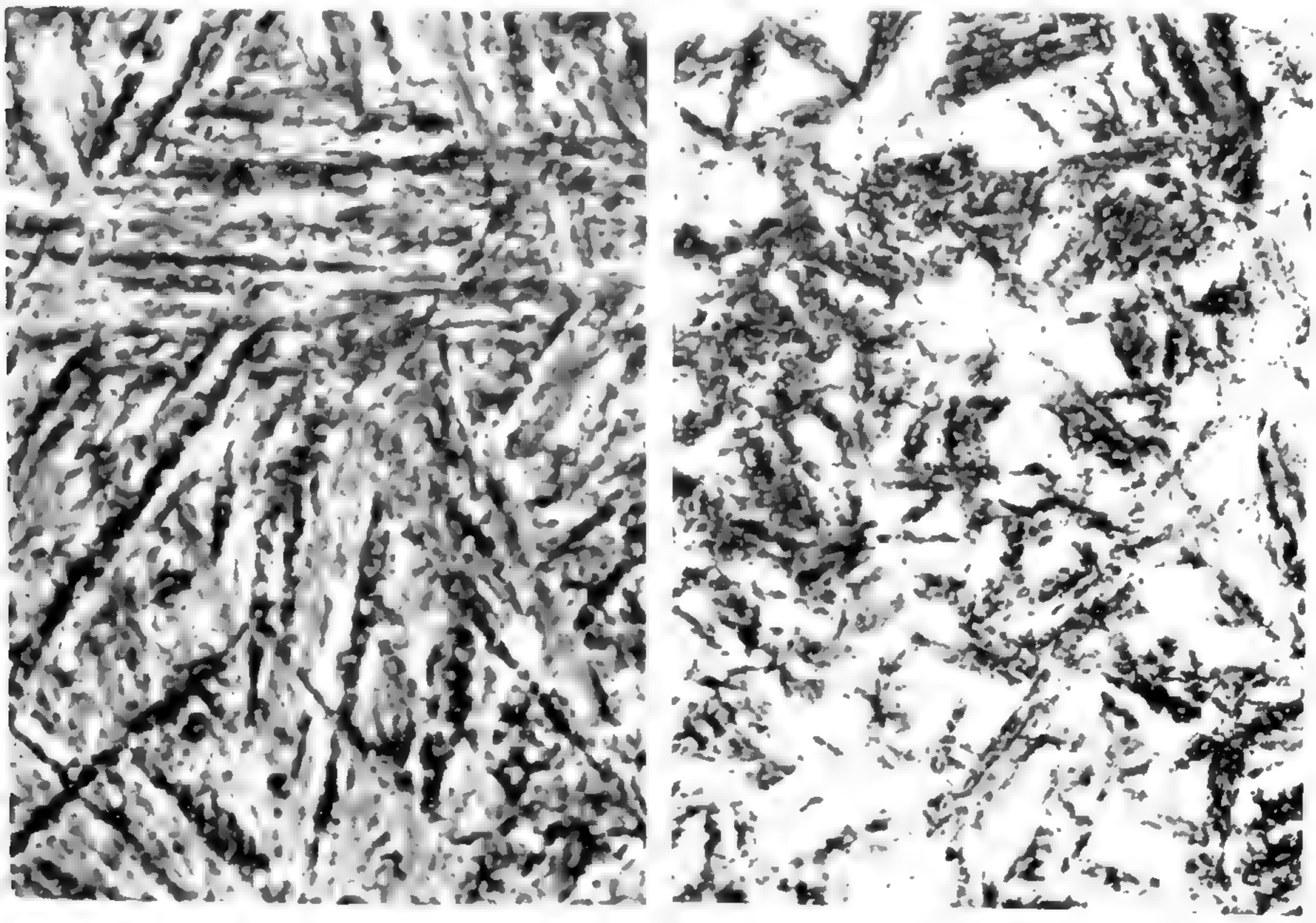
Austenite decomposition is furthered by decreasing the cooling rate from above the upper critical temperature or by subjecting the retained austenite in high-carbon or medium-alloy steels to an isothermal heat treatment below the lower critical temperature range. Studies of the progression of this decomposition with time at various temperatures show that the relationship is not continuously proportional to temperature, but changes in accordance with a transformation curve for each steel. Figure 16 shows the transformation rates for a steel containing 0.35% carbon and 1.85% manganese. Examination reveals that the most rapid transformation occurs at just below

800°F. (430°C.), while just below 1400° F. (760°C.) the time required for complete transformation is quite prolonged. If the isothermal transformation of steel is conducted near but below the A_1 temperature, the first product is ferrite, followed by a coarsely lamellar pearlite. At progressively lower temperatures this product becomes a finer and more nodular pearlite. At a still lower temperature, depending upon the carbon content, acicular martensite appears. The martensite formation is a function of temperature, not time. The percentage of martensite which forms will increase only as the temperature is lowered, with no measurable time lag. An intermediate product of somewhat similar appearance and of high hardness, but with less brittleness than martensite, can be obtained by isothermal treatment within 650 to 750°F. (340 to 400°C.). This is known as *bainite* (Fig. 17).

formation for comparing this process in different steels. Since the time to reach completion after the initiation has been found to vary with the microheterogeneity, this period may differ. In the welding of alloy steels the isothermal tranformation curve which has been determined for many typical steels serves as a guide for proper preheat and postheat temperatures. It is to be noted that continuous cooling will modify slightly the standard isothermal transformation curves.

Change from Ductile to Brittle Fracture

A test which has received a great deal of practical application as a quality criterion is the impact notched-bar bend test. The notched bend test is generally carried out with a square bar (0.394 in. by 0.394 in.) notched on one side with a vee notch of 0.01-in. radius to a depth of



(a) 100% transformed 480°F. 1500 × (b) 50% transformed 800°F. 2000 ×

Fig. 17.—Typical Microstructure of Bainite in NE 8620 Steel

The time required for austenitic decompositon to begin is regarded as the period necessary for nucleation. Some investigators have chosen the time required to complete one-half of the trans-

0.079 in. or with a keyhole type of notch with a radius of about 0.04 inch. The specimen is generally broken with a blow of a pendulum traveling at about 16 ft. per second. The pendulum strikes the

specimen, supported on an anvil, on the side opposite the notch. The notch simply acts to concentrate the stress at its base. In notched bar impact tests, usually the energy required to break the specimen is measured, although frequently the appearance of the fracture gives significant information.

The variation of impact energy with temperature for pearlitic steels generally has the form shown in Fig. 18. There is a range of temperature in which the impact energy suddenly decreases. The type of fracture changes from a fibrous to a bright crystalline one. This transition from ductile to brittle failure generally occurs in the range of temperature from +210 to −150°F. (+100 to −100°C.). Variations in the fineness of the pearlite, the amount of proeutectoid ferrite and the degree of tempering, as well as steel quality, will affect the transition temperature within this range.

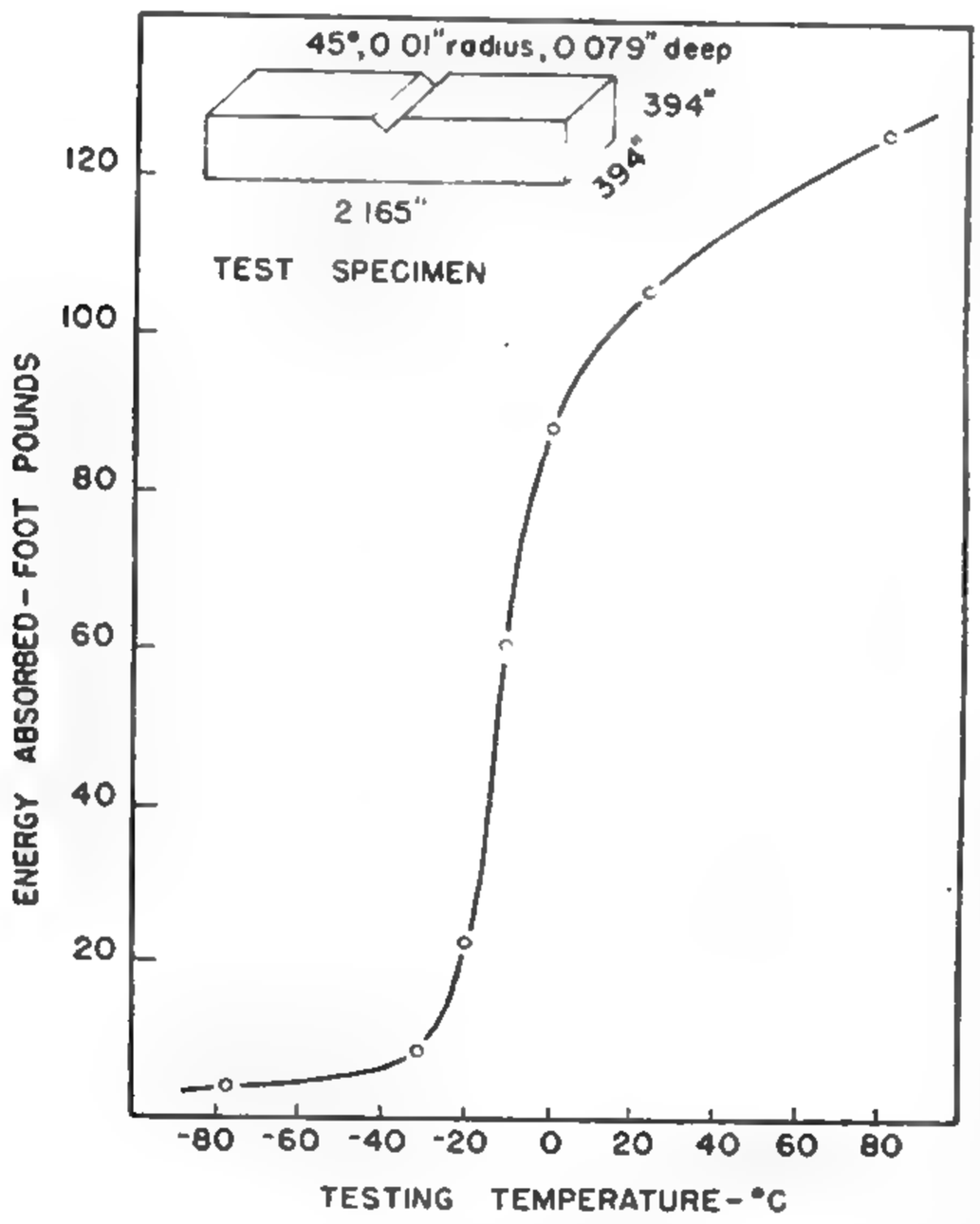


Fig. 18.—Typical Relation Between Testing Temperature and Vee-Notched Charpy Impact Resistance

Transformation at higher temperature, with a coarser pearlite will, in general, decrease the ductile impact energy and raise the transition temperature. Steels made by different processes and having different distributions of inclusions will show different impact energies above the transition zone. The transition zone itself will also be significantly affected by differences in steelmaking practice. Cold deformation, either in tension or compression, will raise the transition temperature.

The effect of specimen size has been discussed in relation to notched bend tests. If a specimen is sufficiently wide with respect to the radius of the notch, differences in energy absorption may arise due to differences in strain rate at the base of the forming crack. However, recent tests on very wide plates indicate that the transition zone for these plates is not much higher than the transition zone observed in vee-notched Charpy specimens of the same material. It seems to be quite evident that the transition from ductile to brittle behavior can be observed using almost any type of specimen. The information can be at least qualitatively interpreted, provided the conditions of test are thoroughly understood. The three most important elements tending to produce a brittle type of fracture are reduced temperature, increased rate of loading and increased restraint. Generally, the temperature at which there is a transition from ductile to brittle fracture in unwelded plate is raised by welding.

MATERIALS

General

Base metals to be welded are limited for practical reasons to the compositions and forms which are amenable to commercial fabrication without appreciable defects. Their weldments should also possess mechanical properties permitting an acceptable construction according to engineering standards. Codes and specifications have been established which restrict the carbon and other hardening elements to insure weldability. This does not imply the inapplicability of steels outside the codes, but indicates their limitations to certain purposes and the necessity of special precautions during the welding.

Usually plain carbon steels utilized in conventional applications are limited to under 0.30% carbon when they are to be welded with ordinary practices. Manganese and silicon contents should be within such limits as to assure a satisfactory practice of steel manufacture, particularly in respect to deoxidation. A

limitation of these elements may be necessary to reduce contribution to any embrittlement in conjunction with other elements. Phosphorus and sulfur are held to the accepted maximum established for the method of steel manufacture which is employed. Other elements are restricted to insure a uniformity of product and an avoidance of unforeseen difficulties in fabrication. Often the composition is limited by a specification of the mechanical properties of the steel.

Weld Metal Composition.—Weld metal consists of fused base metal or a combination of base metal and filler metal and varies with the welding process used. Weld metal that is 100% base metal is encountered in welds in which no filler metal was added, as in resistance welding, welds in edge joints made by gas, pressure gas, inert-gas or carbon-arc welding. Weld metal that is primarily filler metal is encountered in groove welds made by arc and gas welding or in multiple-pass fillet welds. Weld metal that consists of both base and filler metal is encountered in single-pass welds and in welds made by the submerged arc process and the deep fillet technique.

Filler metal, to be added in the molten form to complete a weld junction, is generally used in wire or rod shapes. The chemical composition of the metal used in welding rods and electrodes is usually not specified, except for general type, since normal analysis alone does not indicate their welding properties. The only real criteria of satisfactory performance of welding rods and electrodes are the results of the actual welding operation and the mechanical properties of the deposited metal individually and as a part of the structure. The composition of the filler metal should approach that of the base materials where it is desired to avoid any great discontinuity in physical or chemical characteristics. The composition of the welding rod or electrode is based on expected losses or pickup of elements during the welding operation and upon good welding characteristics. The high temperatures encountered in welding have a great influence upon the welding characteristics of the filler metal if there is any appreciable deviation from the optimum composition established by experience. Electrodes are coated with slag-forming materials. These will reduce losses by atmospheric oxidation or pickup of oxygen and nitrogen, and assure more consistent weld metal properties. Electrode coatings are also desirable to obtain better arc characteristics for welding. Rods for gas welding and those arc welding processes for which they are used are usually uncoated but are protected during welding by the welding atmosphere.

Effect of Atmosphere on Molten State Reactions.—During the welding process the molten metal may react with some of the constituents of the surrounding atmosphere, such as oxygen, nitrogen, hydrogen or the gaseous compounds of these elements with carbon. In bare metal electrodes and welding rods the reaction is direct, but in coated or submerged electrodes the slag is an intermediary during all or part of the molten state periods. Gas shielding using an inert gas is also used to protect the molten metal.

Oxygen.—Oxygen in the presence of molten iron tends to form the ferrous oxide, FeO. Ferric oxides do not exist at elevated temperatures in the presence of liquid iron. Sources of oxygen are the surrounding air, oxides from the coating which are free to react with the molten steel or the dissociation of water present in the air or coating. Bare electrodes may show a little over 0.2% oxygen in the final weld deposit, but of this amount probably less than 0.05% will remain in solid solution at room temperature, the rest being in oxide inclusions. Coated electrodes show much less pickup of oxygen, while in gas welds the final content may be as low as 0.01%. At the melting point, iron covered with ferrous oxide has a maximum oxygen solubility of about 1%. If oxygen-avid elements, such as titanium, aluminum or silicon, are introduced into the molten weld metal, then stable oxides are formed which are not readily reduced by carbon, and the porosity formed during weld metal solidification from carbon oxidation, with the resulting liberation of carbon monoxide gas, is materially reduced. The melting temperatures, viscosities and solubilities of these oxide products may restrict or regulate the use of such deoxidizers in welding operations. Relatively refractory oxides such as aluminum, for example, persist as uncoalesced and undesirable inclusions in the final weld metal

Carbonaceous Gases.—Carbon monox-

ide and some hydrocarbon gases are carbonizing with respect to molten steel, while carbon dioxide and steam are oxidizing. These two opposite effects may practically neutralize each other at a balanced proportion for each temperature. Hydrocarbons and water may be derived from cellulose or other organic ingredients included in electrode coatings, while their oxidation supplies the oxides of carbon CO and CO_2. In oxy-acetylene welding, the oxidizing and reducing gases in the flame may be controlled by proper proportioning.

Reducing or non-reactive gases lower the surface tension of molten weld metal, presumably by preventing the formation of thin but refractory oxide films. By their expansion and convection, liberated gases, particularly those of high thermal conductivity, convey heat away from the arc or other source of welding heat and prevent overheating of the molten metal. This may help to eliminate porosity. Some heat can also be absorbed by the dissociation of polyatomic gases such as hydrogen, but their recombination in cooler zones around the weld may nullify this effect. Rapid gas formation within the molten metal globule, which usually accompanies excessive oxidation, results in high spatter loss because of the violence of its liberation.

Nitrogen.—Nitrogen absorption in molten metal can occur on contact with air, and it is one of the major functions of coating slags to prevent its assimilation. Protective gas atmospheres from gas welding or from organic material in electrode coatings also contribute to this effect. Weld grooves, wide in proportion to welding rod or electrode size may allow greater nitrogen absorption, since the protection by a gaseous envelope is less easily maintained.

As all commercial steels contain some nitrogen, the amount in the weld metal is that in the commercial steel plus the changes due to the welding. In liquid iron or steel, nitrogen concentrations above some 0.04% may be present under equilibrium conditions. Nitrogen up to 0.2% has been observed in bare electrode deposited metal. The more rapid the cooling rate of the molten metal, the higher the final nitrogen content. Covered electrodes usually produce weld metal having a nitrogen content under 0.035%. This value has been established as a maximum for consistent weld metal properties.

Evidence has been offered indicating that nitrogen absorption is increased by an increase in arc length or in the size of the electrode used. It is apparent that the rate of absorption is dependent on dissociation of molecular nitrogen to the atomic form within the arc gap, and any circumstance that affects the arc operation is a controlling factor.

Aluminum, silicon and chromium are believed to aid in the assimilation of nitrogen in steel. Manganese may increase the solubility, but in concentrations characteristic of industrial steels no definite influence can be traced. The final content of nitrogen depends upon its introduction into the molten weld metal, since upon cooling there is insufficient time for a strict iron-nitrogen solubility equilibrium to be attained. The amount of nitrogen in weld metal has been found to decrease with increase in carbon, possibly through gaseous shielding or the sweeping-out action of carbon monoxide evolution.

Inert Gases.—Inert gases are not absorbed to any extent by molten metal and have little effect on the resulting weld. However, they do have a very definite usefulness in welding as a shielding medium, that is, the exclusion of chemically active gases from contact with the molten metal. Inert-gas atmospheres also have considerable effect on the electrical behavior of the welding arc. Doan has shown that in atmospheres of the relatively inert gases, such as argon and helium, high voltages are necessary in order to sustain the arc, there are no pinch effects to aid the detachment of molten globules from the end of the electrode, and no craters are formed in the weld pool. However, the addition of a small amount of oxygen to an otherwise pure inert gas allows the formation of a crater and, consequently, detaches the liquid metal in a succession of small droplets rather than in large globules.

Hydrogen.—Molten metal generally can, and often does, absorb up to 0.005% (by weight) of hydrogen. The absorption of hydrogen occurs atomically. The atomic form may be obtained by the dissociation of water vapor, hydrocarbons or molecular hydrogen by the welding heat or in the electric arc. Hydrogen retained in solution in weld metal may cause localized em-

brittlement around inclusions or defects in low- or medium-strength metals and severe general embrittlement in very high-strength welds. Hydrogen diffuses from the weld metal into the heat-affected zone of the base metal during the welding and cooling period. If the hardenability of the base metal and the rate of cooling of the weld produce a fully hardened heat-affected zone, cracks may occur in this zone. The amount of hydrogen retained in weld metal is controlled by solubility limits and by the reactions liberating gaseous products. Hydrogen diffuses into gas bubbles formed by these reactions, and the retained hydrogen in solution is thus decreased. Porosity, caused by the trapping of gas bubbles in the solidified weld metal, is normally controlled by the relative contents of hydrogen, oxygen, carbon and silicon. Reactions of hydrogen with sulfur and selenium in free-machining steels are also known to cause porosity. (See also section on page 106.)

Weld Metal Cracking.—The majority of cracks that have been reported in weld metal appear to be of a type similar to hot tears in castings. The cracks occur in the early stages of cooling of a single bead and are called *auto-cracks.* Auto-cracks are usually parallel to the direction of welding and, in general, the cracks occur through the thinnest section of the weld. The surfaces of auto-cracks are blued if the cracks extend to the outer surface of the weld. They form at elevated temperatures shortly after solidification of the weld metal. In concave fillet welds, the cracks start at the outer surface of the throat, but in convex fillets, they may start at the root and not reach the surface, thus escaping visual inspection.

Most investigators attribute auto-cracking to low ductility and strength at high temperatures, the weld metal being weaker and less ductile than the cooler base metal. The greater the rigidity of the plates (thickness, tensile strength, clamping) the more frequently auto-cracking occurs, for the weld must undergo greater deformation.

The composition of weld metal is believed to have the following effects on auto-cracking.

Carbon: An increase in carbon content is known to result in a decrease in hot tearing in cast steel. However, increase in carbon in highly killed weld metal slightly increases the cracking tendency in tee joint tests. This observation, together with the fact that hot peening and preheat are effective in preventing the cracks in higher carbon steel deposits suggests that auto-cracking is not involved. Instead, they may be *cold cracks* related to the inability of the hard weld metal to undergo the required deformation under shrinkage stresses acting in more than one direction.

Silicon: Harmful effects of silicon have been observed in the presence of insufficient manganese in weld metal containing 0.22–0.28% carbon.

Manganese: The manganese content of weld metal of itself bears no relation to auto-cracking in the range 0.01–1.0% manganese. Nevertheless, manganese is reported as being of importance in offsetting the effects of sulfur on auto-cracking.

Sulfur: Whether or not sulfur in weld metal promotes auto-cracking depends on the form in which it is combined. Sulfur present as FeS will form a eutectic that does not solidify until 1805°F., hence promoting auto-cracking. Weld metal in which practically the entire sulfur content is combined as MnS is not subject to auto-cracking, unless other additions are made which affect the solubility of MnS in steel, or provide other phases of low melting point.

Phosphorus: Little, if any, effect on auto-cracking has been observed due to phosphorus.

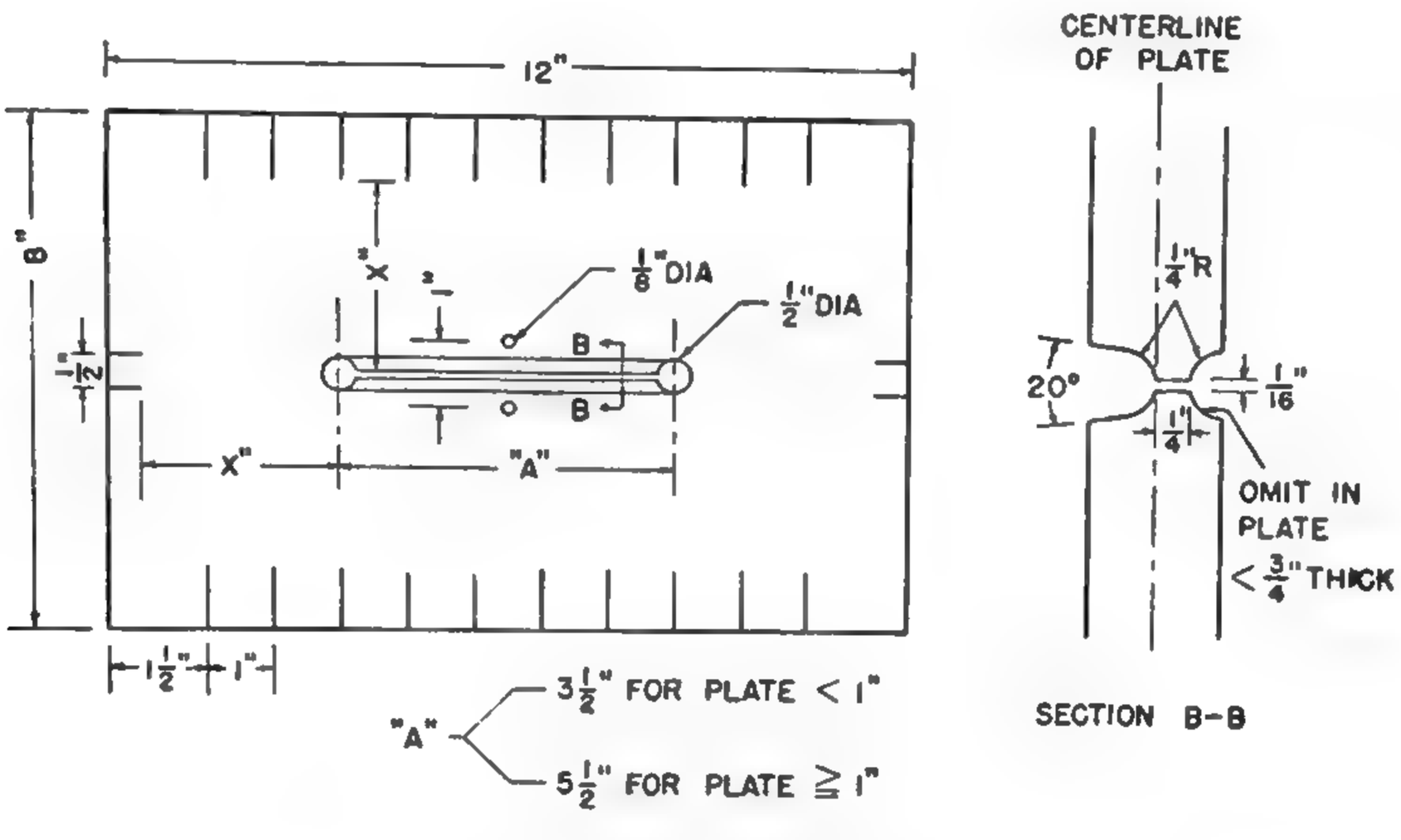
Oxygen: No direct relation has been found between auto-cracking and oxygen content.

Inclusions: Auto-cracking frequently occurs in regions contaminated with slag, while slag-free areas are free of cracks.

Weld Metal Cracking Tests.—The Lehigh restrained cracking specimen was developed for comparing quantitatively the degree of restraint at which cracking occurs in welds during cooling. The test has been shown to be reproducible, and the specimen sensitive to changes in electrode type and brand, plate composition and preheat temperature. The fin-type specimen shown in Fig. 19 is capable of developing sufficient restraint to crack even mild steel plate $^1/_2$-in. thick and, by means of varying the width (distance between the ends of the weakening slots and the cut in the bottom of the U-

groove) in a series of specimens, the degree of restraint can be reduced continuously down to low levels. The width which exists at the threshold of cracking is taken as the index of crack sensitivity. The threshold of cracking is defined as that width at which the weld is just cracked and below which the weld is sound.

The only measurement undertaken in this test was the inward movement of the plate surrounding the weld groove arising from the weld metal contraction.



DETAILS OF THE FIN SPECIMEN

Fig. 19.—Lehigh Fin-Type Cracking Test Specimen

When it was found that the contraction was fairly uniform and quite consistent along the full length of the weld, the contractions were measured at the mid-length of the weld only, using Ames dial gages mounted on pins on the top and bottom sides of the plate. The dial gages, in addition to providing the contraction measurements, were found to provide almost as sensitive a method of crack detection as cross sectioning and microexamination. Thus, the fin-type restraint specimen provides a useful test to indicate that changes in electrode, steel composition and preheat temperature result in significant, quantitative, and predictable variations in cracking tendency. One disadvantage of this test that might be pointed out is the need for a series of specimens in order to determine the threshold of cracking for a given plate material, welding electrode and preheat temperature.

Carbon and Low-Alloy Steels

In general, from the information which is available at the present time, the effect of welding on wrought, forged or cast steels can be considered similar, provided compositions are comparable. The effects of welding upon the base metal can be explained almost entirely in the light of well-known metallurgical phenomena. In order to explain further the effects of the welding process, the following section describes the metallurgical and physical conditions of a simple bead weld. It is not suggested that a bead weld is a typical weld, although it is in many respects very similar to a single-pass fillet weld. The bead weld has had extensive use in testing for weldability and is particularly suitable as it lends itself to definite standardization, permitting variables to be reduced to a minimum.

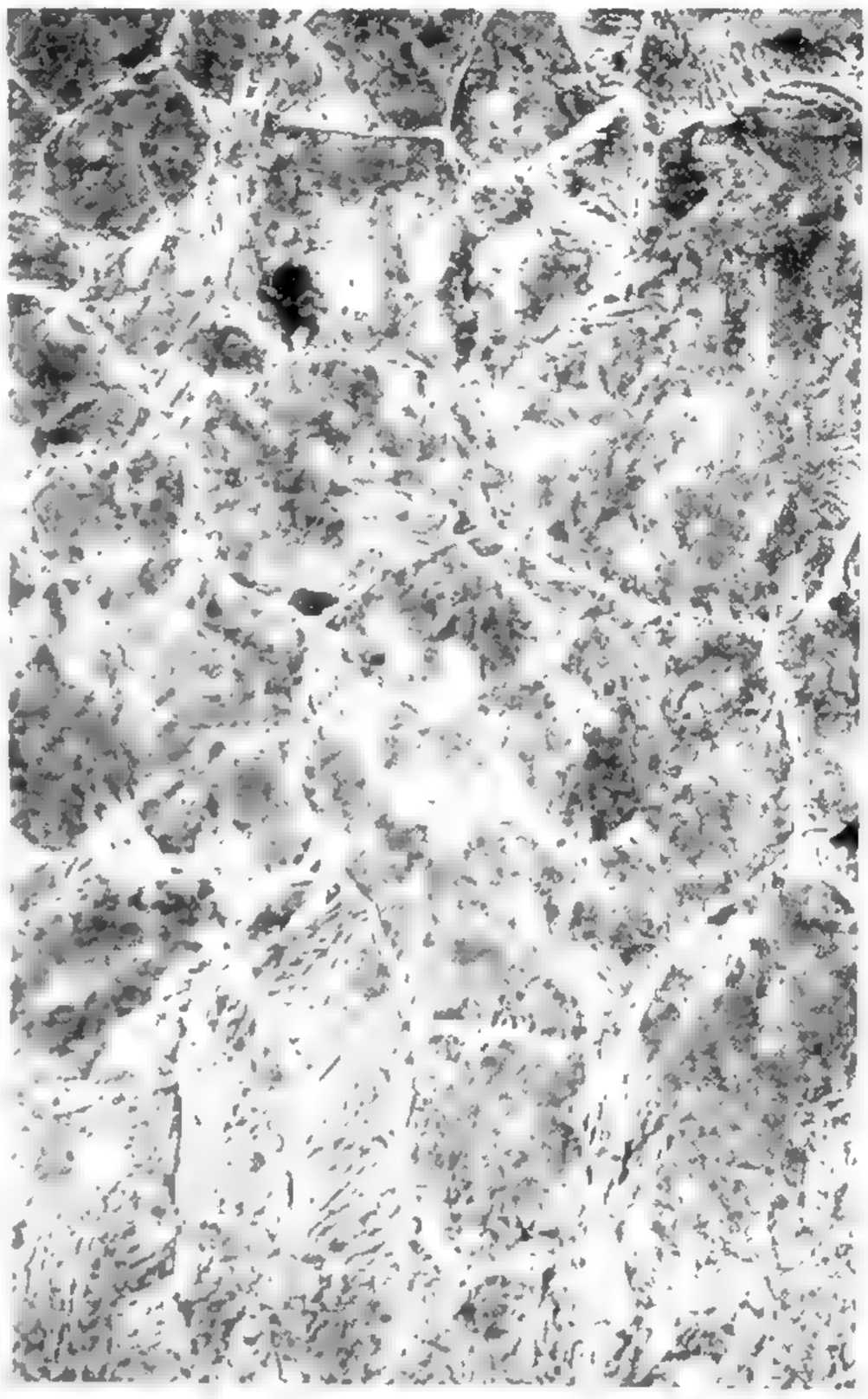
The Bead Weld.—In order that the nomenclature will be understood throughout, the following comments are made regarding a cross section taken transverse to a bead weld. The bead weld cross section is divided into three areas: the plate material or base metal, the heat-affected zone and the weld metal. Plate material refers to the metal that remains unaffected by the weld thermal cycle. The heat-affected zone is that area of the plate material which has been heated by the welding process to temperatures sufficiently high to change the original microstructure

and properties of the material. The weld metal is that area which has been molten and consists of electrode material which has been deposited and plate material which has been melted during welding. The term *penetration*, when used alone, refers to the depth below the original surface of the plate material that has been molten. The boundary between the weld metal and the original plate material is referred to as the *fusion line*.

Any welding procedure will necessarily produce conditions in the base metal comparable to both good and bad heat-treating practice. At the fusion line, the metal has been heated to the melting point and rapidly cooled through the austenitic range by the surrounding mass of metal. The final structure will be dependent upon the composition of the steel and the rate of cooling. The very coarse structure just below the fusion line is a condition typical of overheated steel which has been heated close to its melting temperature, commonly called *superheated steel*. The degree of grain growth associated with welding is the result of the steel having been heated well in excess of the A_3 temperature.

In the area which has reached a maximum temperature below the A_3 temperature and above the A_1 temperature, austenite begins to form, which in turn is transformed during the cooling cycle. For temperatures just below the A_1 transformation the carbide-rich areas tend to coalesce into spheroidal particles. Transformations and attendant metallurgical changes require a definite amount of time but are hastened by increased temperatures. Lower carbon and lower alloy contents will tend to permit the changes to take place in shorter intervals of time. The effects of higher carbon and alloy contents are to increase the sluggishness of transformations and to decrease the critical rate of cooling

In a study of the grain size which results in the coarsened area of the heat-affected zone (Fig. 20), considerable variation will be found in the behavior of various materials. The grain coarsening will depend upon the temperature and length of time at temperature which in turn depends upon the thickness of material and welding technique employed. The presence of grain-refining additions such as vanadium and titanium will, in general, restrain the grain growth in the coarsened area. To complicate matters, the grain size under the bead varies from one location to another and, at the same time, variations in grain size will be found to influence the mechanical properties of the heat-affected zone. Some attention has been given to the differences in the width of the heat-affected zone;



100 ×

Fig. 20.—Coarse Grain in Heat-Affected Zone Adjacent to Deposited Weld Metal

a narrow, hard zone cushioned by softer zones is not so critical as a wider zone of somewhat lower hardness. As the heat-affected zone may act as a notch, consideration of the transition temperature behavior of a steel having a bead or fillet weld becomes important since the transition from ductile to cleavage-type fracture is dependent upon the degree of stress concentration.

Effect of Multiple Passes.—The above description relates to a single-pass fillet weld or bead weld. The metallurgical effects will be modified in heavier joints in which multiple beads or passes are deposited in a groove in order to increase

the weld volume to the full thickness of the base metal. Here, however, the first pass or bead is essentially a single bead, and its metallurgical effect will be identical with that described above. Additional beads or passes deposited before the plate has cooled to room temperature will be accompanied by less drastic thermal changes. If the plate is allowed to cool to room temperature before the second pass is deposited, the thermal cycle will again be almost identical with the previous condition. This thermal cycle will have its influence on the previous structure, since reheating will temper or reharden the structure, depending upon the temperature attained. An attempt is often made to deposit each layer in such a thickness that the grain structure of the previous pass will be largely refined. Often the final layer will consist of three beads, the first two being deposited along the scarves, and the third bead between these two. In this manner, the zones of highest hardness in the plate will be tempered to a lower hardness with improved ductility.

Evaluation of Effect of Welding on Base Metal.—The welding engineer is constantly confronted with the problem of not only selecting materials but also determining the proper welding methods and techniques to fabricate the materials into a suitable structure. Weldability tests are required in any program to develop or select weldable material or to determine optimum methods and techniques for welding operations. The development of tests for measuring the relative weldability of a steel has been the subject of extensive investigation. The factors which must be considered in the design or selection of weldability tests are numerous. The specimens should not be complicated in design, and it is desirable that a minimum amount of machine work be required. Test methods should be reproducible and have sufficient sensitivity so that the effect of changes in welding technique may be detected. Tests should also distinguish between the differences in the weldability of similar materials and be adaptable to studies including variations in thickness of the material. Finally, tests should be designed to approach the service requirements of the structure so far as rigidity, rate of loading and temperature are concerned.

Any welding procedure is complicated by a large number of variables, such as energy input, preheat and postheat temperatures, electrode type and diameter, chemical composition and mechanical properties of the base metal, welding sequence, joint design and constraint of the structure. In an attempt to simplify laboratory procedures, investigators usually consider only one or two of the variables at a time. This has brought about considerable confusion in the interpretation of weldability testing since each proponent of a test interprets his results in the light of the variables which he has used in his investigation. In the comparison of tests, many of the methods of evaluating weldability will rate materials or procedures qualitatively in the same order—a quantitative evaluation is much more difficult.

Another consideration, that is paramount in testing for weldability, is the fact that most tests are laboratory tests from which it is desired to predict the performance of a material or process in a large structure. The relationship of small-scale laboratory tests to performance in the field structure, however, has not been quantitatively established. Only recently, testing temperature, degree of constraint and rate of loading have been associated with the transition from ductile to brittle or cleavage-type fracture. It now appears that these factors will aid in establishing a quantitative relationship between large-scale and smaller-scale laboratory tests.

Broadly speaking, a test for weldability consists of subjecting the material to the temperature cycle involved in the welding process and then evaluating the ductility of the resulting structures. The thermal cycle may be that obtained by an actual welding operation, or the effect of welding temperatures may be simulated by subjecting test samples to special heat-treatment routines.

The technical literature reveals that there are over fifty different specimens which have been used to evaluate some of the characteristics of weldments. These tests fall into four major categories: (1) weld metal tests, (2) tension tests of joints, (3) bend tests and (4) fatigue tests. There are those tests that measure directly the effect of welding on the ductility of a steel, and also those that observe a change in some property, such as the maximum hardness

of the heat-affected zone, and assume a direct correlation between this change and the resultant ductility.

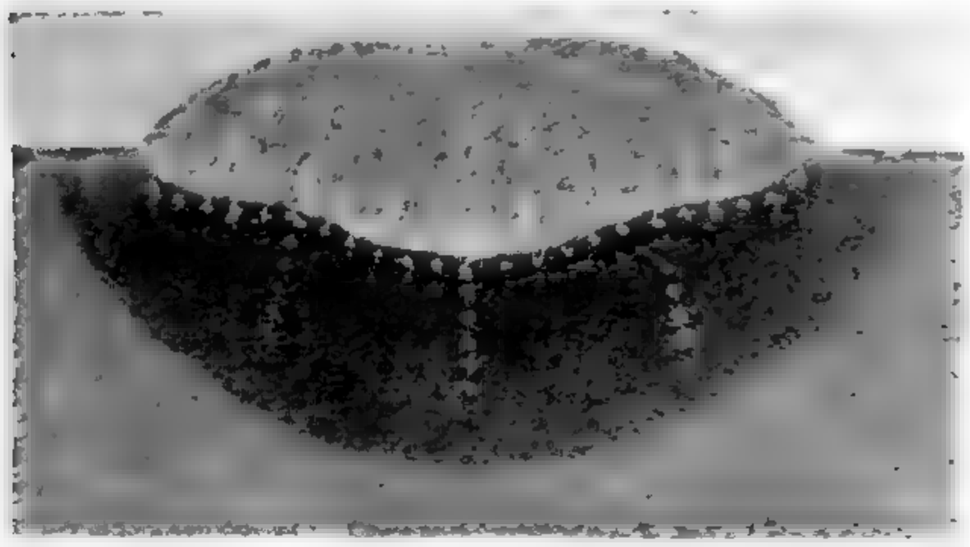


Fig. 21.—Section of Bead Weld Showing Vickers Hardness Survey

The early tests for evaluating the suitability of a particular welding process for joining a particular type of material usually consisted of making a sample joint. The ductility of the resulting joint was then measured by tensile testing or bending. Such testing is still used in many applications for procedure qualification, and the performance often depends upon the skill of the operator as much as upon the suitability of the procedure.

The hardness developed in the heat-affected zone contiguous to a weld deposit has attracted considerable attention. Usually, the hardness of a transverse section of the heat-affected zone is explored by means of an instrument such as the Vickers, Knoop or Eberbach hardness tester. Several investigators have obtained considerable data from this simple test, and it is almost universally used in conjunction with any other tests that may be performed (Fig. 21). The maximum hardness method has always found wide use, since a hardness survey requires a minimum of initial specimen preparation, and, similar to microscopic examination, imposes no limitation on welding technique and thickness of material. Its success, however, depends entirely upon the assumption that there is a satisfactory correlation between maximum hardness and ductility (Fig. 22).

In many studies, in order to obtain additional information regarding the heat-affected zone, microscopic examinations were made of structures resulting from the welding thermal cycle, on the assumption that ductility could be predicted from a careful evaluation of these structures. In general, such an evaluation for steels covering a wide range of weldability is not difficult, but specific, quantitative interpretation of results for steels over a narrow range of weldability is almost impossible. However, a microscopic examination of the cross section of

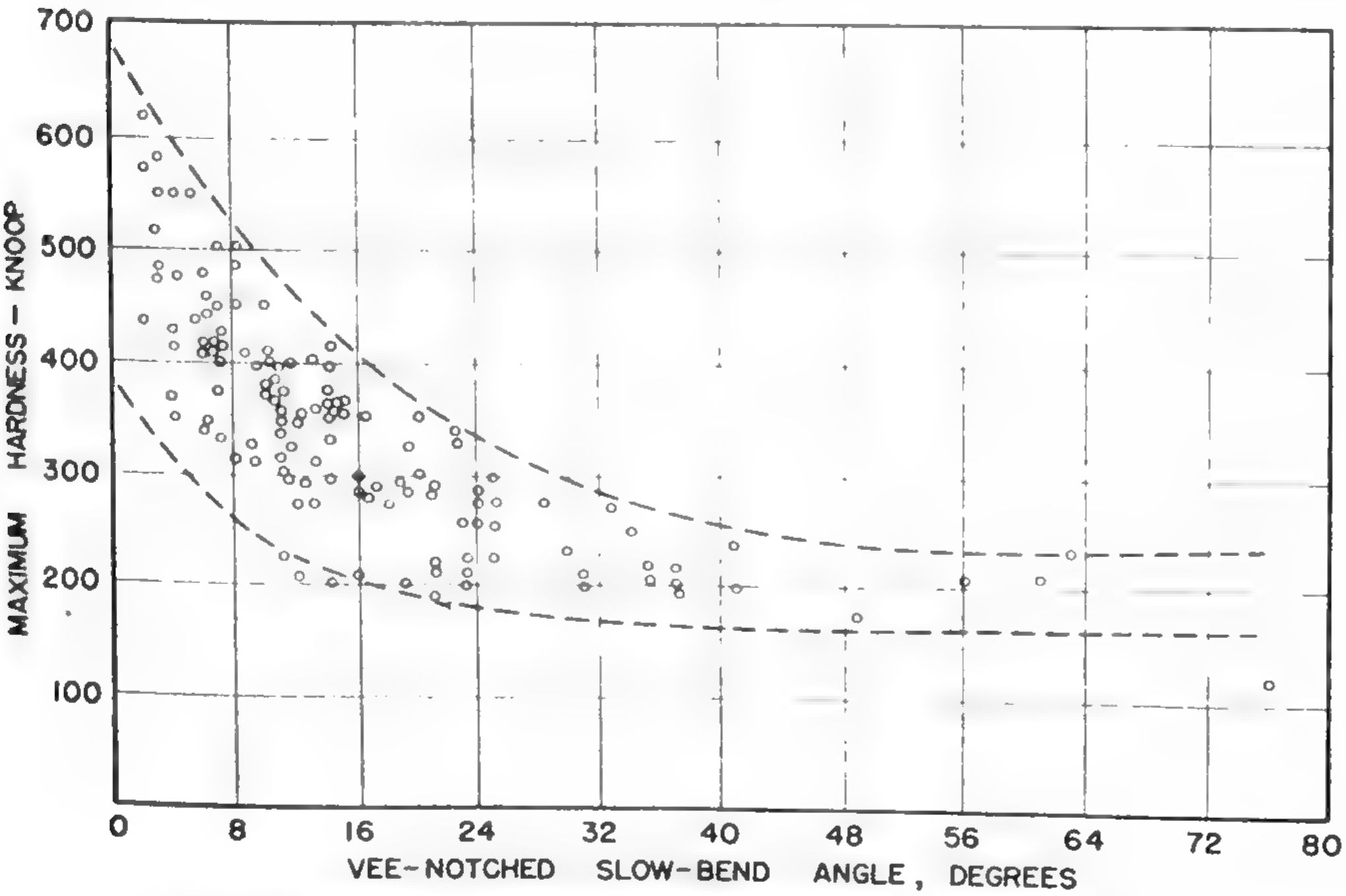


Fig. 22.—Relationship Between Maximum Hardness and Bend Angle

a weld accomplishes the following purposes: (1) it discloses both the quality and structure of the weld metal deposit and the metallurgical structure of the heat-affected zone, which enables the metallurgist to evaluate the cooling rate; (2) it provides a means of detecting microcracks; and (3) it permits the detection of segregation, laminations and inclusions in the steel. Such observations furnish pertinent information in any weldability study. Again, as in the use of the maximum hardness test, a microscopic examination must be made in conjunction with some other weldability test in examining steels over a narrow range of weldability.

Studies of the thermal conditions and the metallurgical effects at the rates of cooling in the welding heat-treatment cycle, have been frequently suggested. These data, together with the accepted views of metallurgical changes, may be used to predict the resulting ductility. Considerable attention has been given to the possibility of the application of isothermal and continuous cooling transformation studies. In all cases, an attempt has been made to evaluate the change in ductility of structures resulting from the heat treatment of the steel by the welding thermal cycle. A number of investigators have been interested in the use of the temperature relationships in the heat-affected zone and their metallurgical effects as a means for evaluating weldability. Aborn has pointed out that the properties of the heat-affected zone are the result of structural changes which are determined at any point by the maximum temperature, the length of time at that temperature and, more particularly, by the subsequent rate of cooling at that point, for this rate, if too great, will produce a zone of undesirable structure.

Hodell and Bruce developed formulas which were used to predict and control temperatures in the welding of an oil-well casing. An experimental program was carried out to measure the actual temperatures of cooling welds in the casing, and a close agreement was found between the analytical and experimental cooling curves. Hess, Merrill, Nippes and Bunk undertook the measurement of actual cooling rates in the heat-affected zone of single-vee groove welds. These data were used to modify fundamental mathematical solutions, and tables were prepared showing the energy in joules per inch required to produce any desired cooling rate at any selected temperature level for plate temperatures ranging from 37°F. (3°C.) to 400°F. (204°C.) and for plate thicknesses of $^1/_2$, 1 and $1^1/_2$ inches.

A number of tests have been suggested in which special heat-treatment techniques are used in an attempt to produce specimens with microstructures similar to those observed in the heat-affected zone.

One of the widely used direct tests for evaluating weldability is the tee-bend test sponsored by Bibber and described by Ellinger, Bissell, and Williams. A double fillet welded tee joint (Fig. 23)

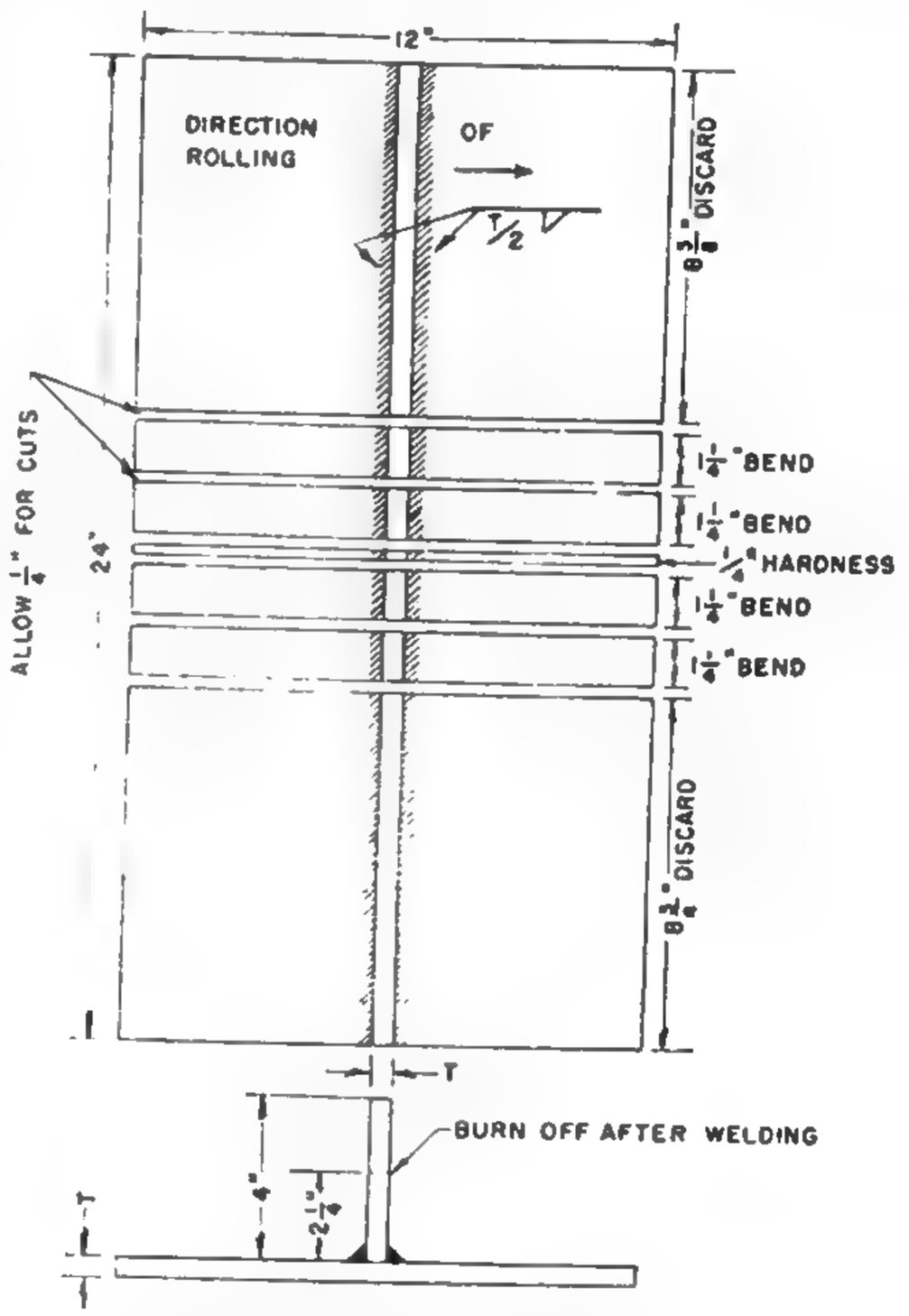


Fig. 23.—Tee-Bend Test Specimen

is tested as a guided bend specimen without removing any metal from the face of the weld. A special jig (Fig. 24) is used for bending the specimens, and the angle of the head of the tee at maximum load is recorded, together with the load and type of fracture at failure. Bibber and Hueschkel have suggested that the measurement of the energy absorbed in the bending is an additional index. It is interesting to note that the tee-bend test was the first test to differentiate between high-strength and low-strength steels.

This was also the first of the bend tests requiring consideration of mode of failure, that is, ductile or brittle. It was felt that those steels which failed with a brittle fracture were less desirable for a welded structure, even though the angle at maximum load was satisfactory. The early investigators showed that the temperature of testing had an important effect on the angle of bend and mode of failure. It was felt that the tee-bend test integrated in the performance of a welded joint, the quality of the base metal and the effect of the welding. There was no procedure for comparing base metal and welded specimens. Usually, this testing procedure is applied to comparatively low-hardenability structural steels, such as used in ship construction. However, there has been at least one attempt to apply the test to materials with higher hardenability, such as steels used in aircraft construction.

Kommerell and Bierett suggested an unnotched, longitudinal, bead weld specimen for determining the weldability of a manganese structural steel. The specimen, larger than those subsequently used by American investigators, was tested statically in a bending jig with the weld in tension. Two methods of evaluating the test were employed: the measurement of the angle at which cracking first propagated into the base metal, and the classification of the type of fracture either as a sudden fracture without appreciable previous deformation or as a gradual fracture after the development of a considerable degree of bending. In the early work of Kommerell and Bierett, the stipulation of a determinate bending angle was rejected, and it was required simply that the longitudinal, bead weld specimen should not exhibit any signs of brittle fracture. The test was generally considered extremely severe but, nevertheless, useful in evaluating the sensitivity of a steel to welding. However, difficulty was experienced in selecting an index which would be agreed upon as a guide to weldability. A recently reported investigation by Graff, using the above test, states: "As a specification test for 2-in. wide flange steel in the steel mill, it is recommended that a bend angle of at least 50 deg., better 60 deg., must be reached without fracture."

American investigators have found the longitudinal bead weld, slow-bend test to be probably the simplest and most flexible of all ductility tests in lighter-gage, high-strength materials, such as aircraft

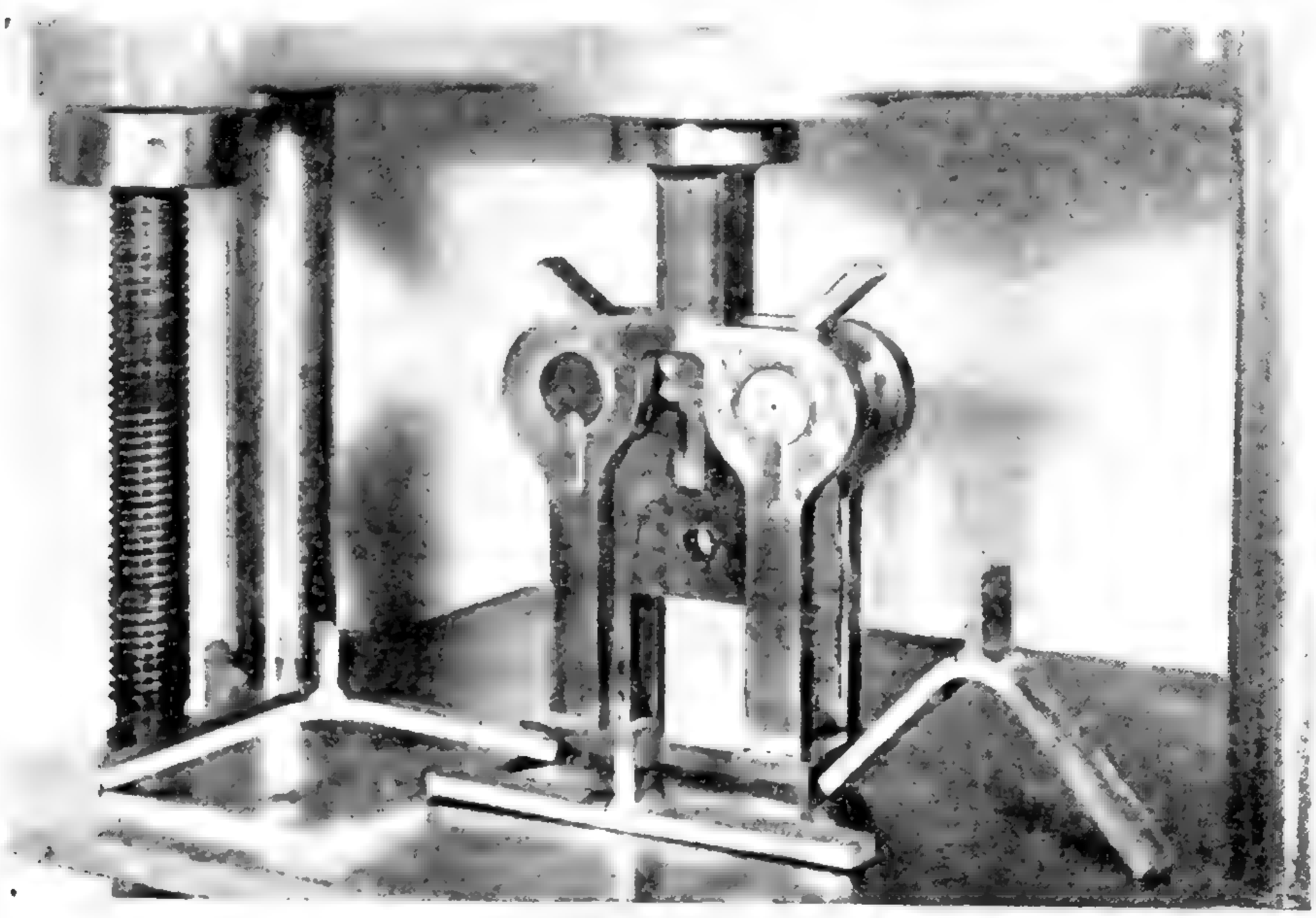


Fig. 24.—Tee-Bend Test Jig

steels. However, the success of the test in low-carbon steels is confined to the heavier gages. A modification of the longitudinal bead weld specimen, gaining popularity in this country, comprises the use of a notch across the welded area, and more will be said later in this section relative to the application of the test in studying the effects of welding on steels.

Cornelius and Fashsel developed a notch-bend specimen comprising a transverse bead weld with a parallel notch machined so that its apex touched the fusion line. The specimen was bent around a pin until the first appearance of a crack at the root of the notch. The angle of bend at failure was considered to provide a measure of the ability of the material in the heat-affected zone to undergo plastic deformation. This specimen has been modified by various investigators, in an attempt to develop a test method in which the effect of welding on the behavior of the plate material can be compared with that of the unwelded plate. The slow-bend test is applicable to any thickness of steel plate, and the welding technique may be varied to suit practical limitations. It has been modified in a number of ways, including dimensions of the test specimen and the type of notch. Luther, et al., presented the results of an investigation of the effect of welding on the temperature at which a change from ductile to brittle failure occurred. It was found that for a number of steels the temperature at which there was a transition from a ductile to brittle type of fracture in the unwelded plate was raised by welding.

One of the most intensive researches on steel weldability has been that concerning *hard* or *underbead* cracking in the heat-affected zone of base metals in metal-arc welds. A number of test methods have been proposed for determining the underbead cracking tendency for a particular steel. Most of these have been more or less qualitative since wide variations usually cannot be avoided in the results.

Swinden and Reeve showed that, if severe restraint is imposed upon a welded joint in a low-alloy steel, cracking may result in the hardened zone. In addition, they described a restrained welded test piece which could be used to determine the conditions required to produce cracking. The test fillet of the Reeve specimen was made while restrained by previous construction. The development of this test was probably the first important step in the recognition of the need for measuring the crack sensitivity with respect to a restrained condition. Luther, Laxar and Jackson have described a cracking test based upon the degree of cracking in the heat-affected zones contained in cross sections of bead welds (Fig. 25). Transverse microsections were examined, and the amount of cracking present was qualitatively used as an index. Investigators at Battelle Memorial Institute and elsewhere have examined longitudinal sections of this same type of specimen in order to express the degree of cracking in percent of total length of the bead. No rigorous quantitative method has been developed.

The results of a number of investigations lead to the conclusion that cracking in the heat-affected zones can occur whenever a critical combination of four factors is present. These factors are hydrogen, rate of heating and cooling, chemical composition and structure, and stress. Suitable techniques reported for the control of cracking are:

1. Choose a ferritic electrode whose coating contains a minimum of hydrogen and/or water-bearing ingredients.
2. Choose an austenitic steel electrode.
3. Select a suitable preheating temperature, welding heat-input or post-heat treatment to insure that, after welding, the tranformation of austenite in the heat-affected zone can be made to occur at a high enough temperature so that martensite will not form or that hydrogen diffuses away from zones of high hydrogen concentration.
4. Choose a steel of minimum carbon and alloy content permitted for the particular service requirement.

The investigation conducted by Doan, Stout, Frye and Tör provides an illustration of a systematic approach to the evaluation of the weldability of a steel. This work is significant, since for the first time an overall system was suggested for evaluating the weldability of a steel. The basic ideas presented in the tentative system for preserving ductility in weldments may be summarized as follows: (1) when a steel is welded, a definite maximum hardness is obtained which is dependent upon the cooling rate imposed by the welding operation; (2) equivalent hard-

nesses in the heat-affected zone and in the Jominy end-quench test bar may be taken to indicate equal cooling rates; and (3) each position on the Jominy bar represents a definite cooling rate and, consequently, corresponds to a certain combination of welding conditions. Therefore, equivalent hardnesses may be substituted for cooling rates, and the hardness may be expressed in terms of Jominy distance. A notched bend specimen was used to establish the ductility hardness relationship since it was felt that ductility also should be made a criterion for the hardened zone instead of hardness alone. The welding conditions were made universal with respect to joint geometry and plate thickness by virtue of having been modified by Stout's geometry factor.

An alternate method was later proposed which eliminated the use of the Jominy specimen and substituted for it a direct welding test in the form of simple bead-on-plate welds. Beads were deposited on plates with each bead deposited at a different energy input. The resulting variation in cooling rates with varying energy levels was reflected by a change in maximum hardness of the heat-affected zone of the base metal. As before, the bend angle accompanying each hardness level was then determined by a set of specimens cooled at different rates.

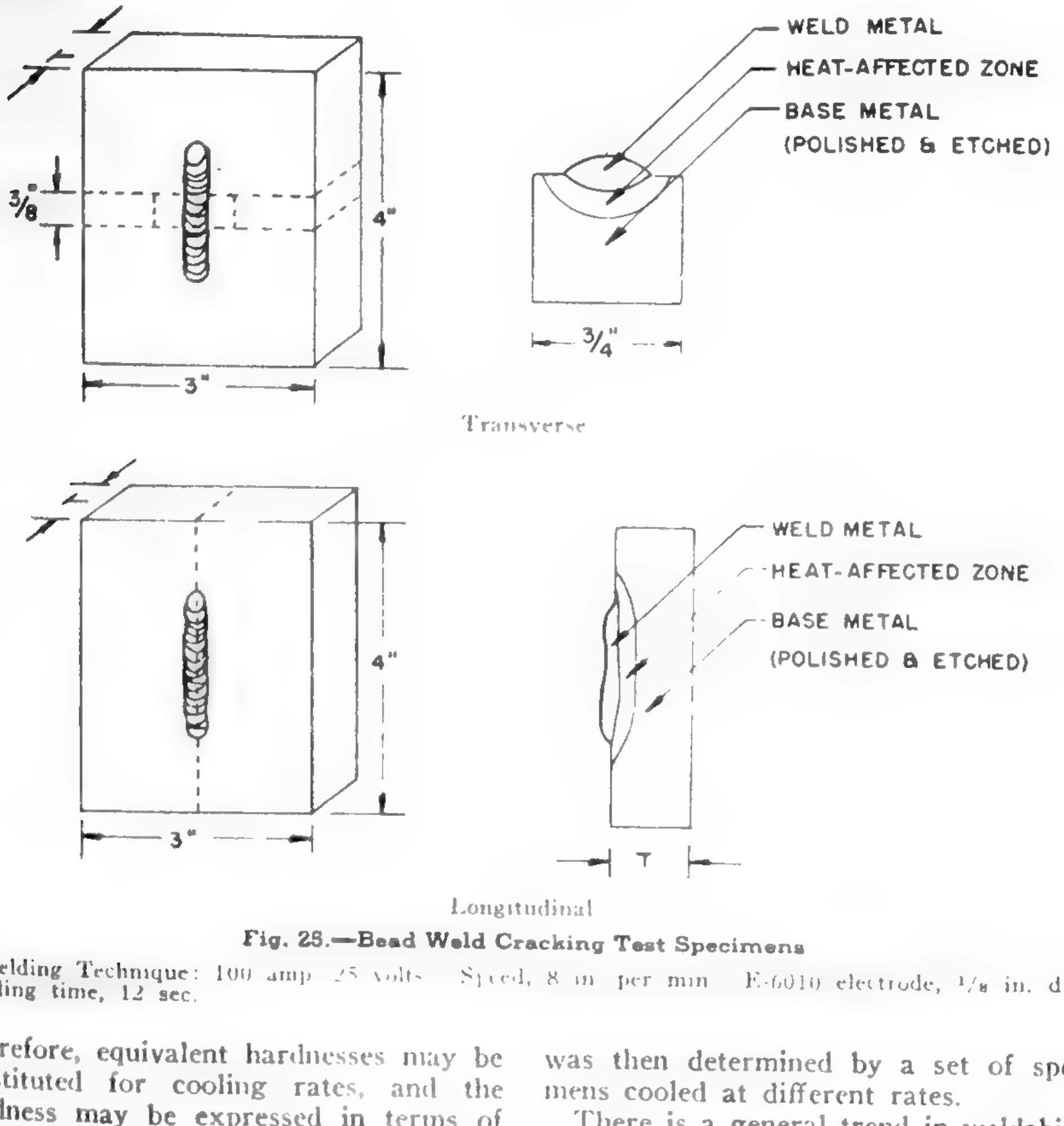


Fig. 25.—Bead Weld Cracking Test Specimens

Welding Technique: 100 amp 25 volts Speed, 8 in per min E-6010 electrode, 1/8 in. diam. Welding time, 12 sec.

There is a general trend in weldability testing toward the use of low temperatures as a determining variable, and all of the recent investigators consider that service performance of a steel or weldment is related to its transition temperature. The relationship between service performance and the temperature at which a bend specimen or other type changes from a ductile to a brittle type of fracture has been studied by many investigators in this country. They have explored with unwelded plate, and a few have shown the importance of the effect of welding on the transition temperature.

One of the earliest investigations con-

cerned the effect of temperature on the angle of bend of welded specimens (Houdremont, Schonrock and Wiester). They showed an increase in angle of bend from less than 20 deg. to over 100 deg. as the temperature of testing increased from 68 to 212°F. (20 to 100°C.). In this country a group at Massachusetts Institute of Technology, initially under the late Prof. A. V. de-Forest, undertook to investigate this method of approach to the weldability problem.

Much effort has been directed toward the determination of completely brittle fractures. It has been shown that the shape of the test specimen, the degree of constraint, the rate of loading and the temperature of testing were important in the investigation of any given material. Stout and McGeady investigated the effect of a number of variables on transition temperature. They showed that the most important variable which influences the properties of notch sensitivity and ductility of structural steels is the variation of the steel itself from one heat to another. Further, it was shown that the properties of the unwelded plate are not a reliable indication of the properties which will result when welding is performed on the plate. It is becoming increasingly evident, through continued research, that when structural steels are heated by welding to temperatures within the critical range and then cooled moderately fast, high notch sensitivity characteristics are obtained. Anderson and Waggoner reported an investigation on the behavior of welded structural steel and on brittle fractures under service loading. They obtained a brittle fracture with some 2% elongation or reduction of area. They mentioned that due to restraint in a structure, accompanied by low temperatures, the yield strength of a structural steel can be raised to the ultimate strength, and that this eliminates the possibility of plastic yielding.

Luther, Jackson and Hartbower reported the effect of welding on the transition temperature of a number of steels but found difficulty in correlating the results, since various test specimens indicated different performance. In a summary of welding tests of carbon and low-alloy steels, these same authors point out the need for fundamental information relative to the phenomenon of transition temperatures in steels and the factors that influence them.

Recently, a rather extensive report on the fracture of metals was prepared by Gensamer, et al. This survey was prepared and reported in order to form the basis for a long-time research program on the subject. The extensive discussion further emphasized the fact that, even in homogeneous materials, the theoretical considerations and mechanism for transition temperature from ductile to brittle behavior are not well understood. The fact that almost 300 references were cited, further emphasized that considerable investigation and thought have been given to this field. It is mentioned that the most important factors which affect flow and fracture strengths appear to be stress combination, type of load, plastic strain, history, temperature, rate of strain, composition and metallurgical structures. At the present time, it is impossible to quantitatively evaluate the effect of these various factors. In some cases, a qualitative statement may be made regarding the influence of a particular factor. Gensamer's statements have been related to the performance of the base material alone and have not considered the effect of welding on the base metal properties. Welding complicates the problem.

In the final report of a Board of Investigation entitled *The Design and Methods of Construction of Welded Steel Merchant Vessels,* it was concluded that the fractures in welded ships were caused by notches and by steel which was notch sensitive at operating temperatures. The highest incidence of fracture occurred under the combination of low temperature and heavy seas. It was felt that improved behavior can be provided by improved steel characteristics.

As a result of the failure of welded ships, extensive investigations of ship steels have been directed toward studying the mechanical and metallurgical aspects of the failures. These tests have included large- and small-scale specimens. In fact, tests have included vessels in service, replicas of welded hatch corner construction and all the standard and many ingenious non-standard test specimens. At the present time, the mechanism of metal fracture is not well understood although concepts, such as the relation of resistance to flow and fracture and the change from ductile to brittle behavior with de-

creasing temperature, are being studied in attempts to elucidate the mechanism of brittle fractures.

In the past, the notched-bar impact test has been used occasionally as an index of the ability of material to deform plastically under service conditions. The correlation has not been satisfying. A new approach to the phenomenon of plastic deformation has resulted from the greater understanding provided by recent experimentation, such as the work at Watertown Arsenal by Hollomon and Zener. For ferritic-pearlitic steels, the interrelation of radius of the notch, rate of applied load and temperature for plastic flow has been qualitatively proved and quantitatively indicated.

Bagsar, Kahn and Imbembo proposed cleavage-tear tests in which a notched tensile-bend type of test coupon was used. The effects of notch and coupon geometries, load eccentricity, rate of loading, testing temperature, and of heat treatment were indicated by the more fundamental work of Bagsar, whose test method is based upon a coupon which has sufficient rigidity and sharpness of notch to assure development of cleavage fracture consistently. The test method proposed by Kahn and Imbembo was intended to define transition from shear to cleavage fracture in a manner which correlates with large-scale plate tests or simulated service tests rather than to induce cleavage failure under all conditions.

One of the most recent works reported on ductility of steels for welded structures was the ASM Campbell Memorial Lecture presented by Kinzel in 1947. Kinzel concurred with contemporary investigators in that the trend in weldability testing is to use low temperature as a determining variable and to recognize that service performance of a steel structure is related to its transition temperature.

The phenomenon of decreased ductility with decreasing temperature was observed in many types of specimens. The choice of a particular specimen was dictated by ease of machining and testing. The test specimen and the method selected for comparing the embrittling temperatures are shown in Fig. 26. The specimen was tested in static loading as a simple beam loaded in the plane of the notch (Fig. 27). The criterion suggested for the development of a brittle state or condition in a bend-test specimen is the lateral contraction at the fracture. The embrittling temperature was defined as that at which approximately 1% lateral contraction occurred. The ratio of proportional limit to the maximum load approached unity under conditions that produced about 1% lateral contraction at fracture.

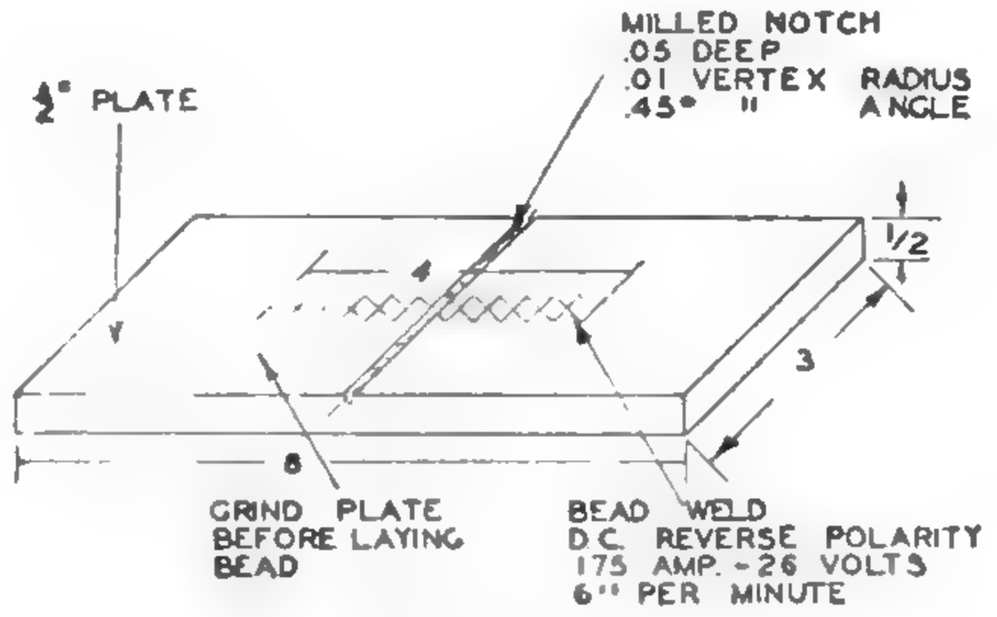


Fig. 26.—Slow-Bend Test Specimen

It was demonstrated that lowering of ductility with lowering of temperature is in no instance a proportional relationship. In some of the steels, the lowering of ductility with temperature was gradual over a wide range of temperature. In many others, slight lowering of ductility occurred as the temperature was lowered until some rather narrow critical range of temperature was reached, when the loss of ductility was extremely rapid with lowering temperature as shown in Fig. 28.

Results of tests wherein other factors than temperature were varied showed (as expected by theory) that higher velocity of testing and greater degree of restraint acted in the same direction as lowering the temperature of test, that is, in increasing the proportion of the fracture which exhibited a brittle, coarse, crystalline appearance.

One of the findings of these comprehensive tests of most interest to designers, therefore, was that the deleterious effect of restraint in a structure has not been overemphasized in recent literature. In this regard, the welding engineer also has great responsibility to specify the proper cycle of operations to minimize the restraint imposed by the differential heat effects of the welding operation, and to insist on proper preliminary heat treatment (normalizing) or postheat treatment (stress-relief) when the necessity is indicated. Previous statements notwith-

standing, there is probably little doubt that the quantitative relationship between small-scale laboratory tests and the performance of full-scale structures can be established only by the systematic laboratory investigation of small-scale specimens run concurrently with tests on large-scale members that actually represent elements of a full-scale structure. Similar tests might be performed on actual failures as post mortem studies of the behavior of the casualty structure.

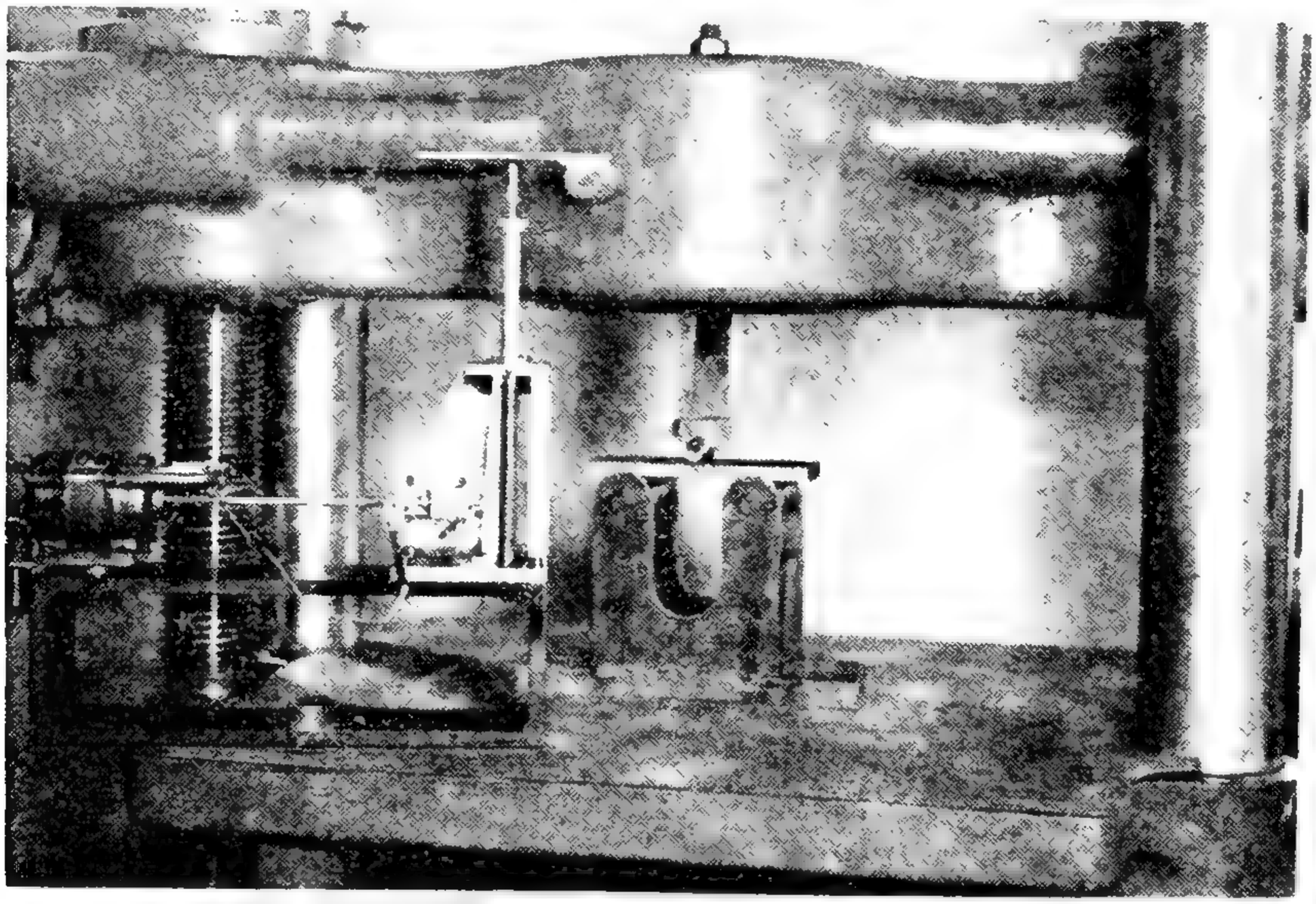


Fig. 27.—Test Jig and Load Recorder for Slow-Bend Test

Summary of the General Metallurgical Effects of Specific Elements

It has been previously stated that from the standpoint of actually making the welds, almost any homogeneous structural steel that can be made can be welded provided that appropriate welding conditions are employed.

Welding involves the localized heating or melting of the metals to be joined, and the joint is necessarily subjected to a steep temperature gradient in a relatively small mass of metal. The elements that are combined in the chemical composition of each steel very definitely influence the thermal effect of the welding operation.

A list of most of the elements involved, metallic or otherwise, that are of interest to the producers and fabricators of carbon and low-alloy steels, is as follows:

Carbon	Molybdenum
Manganese	Vanadium
Phosphorus	Aluminum
Sulfur	Titanium
Silicon	Zirconium
Nickel	Oxygen
Copper	Hydrogen
Chromium	Nitrogen

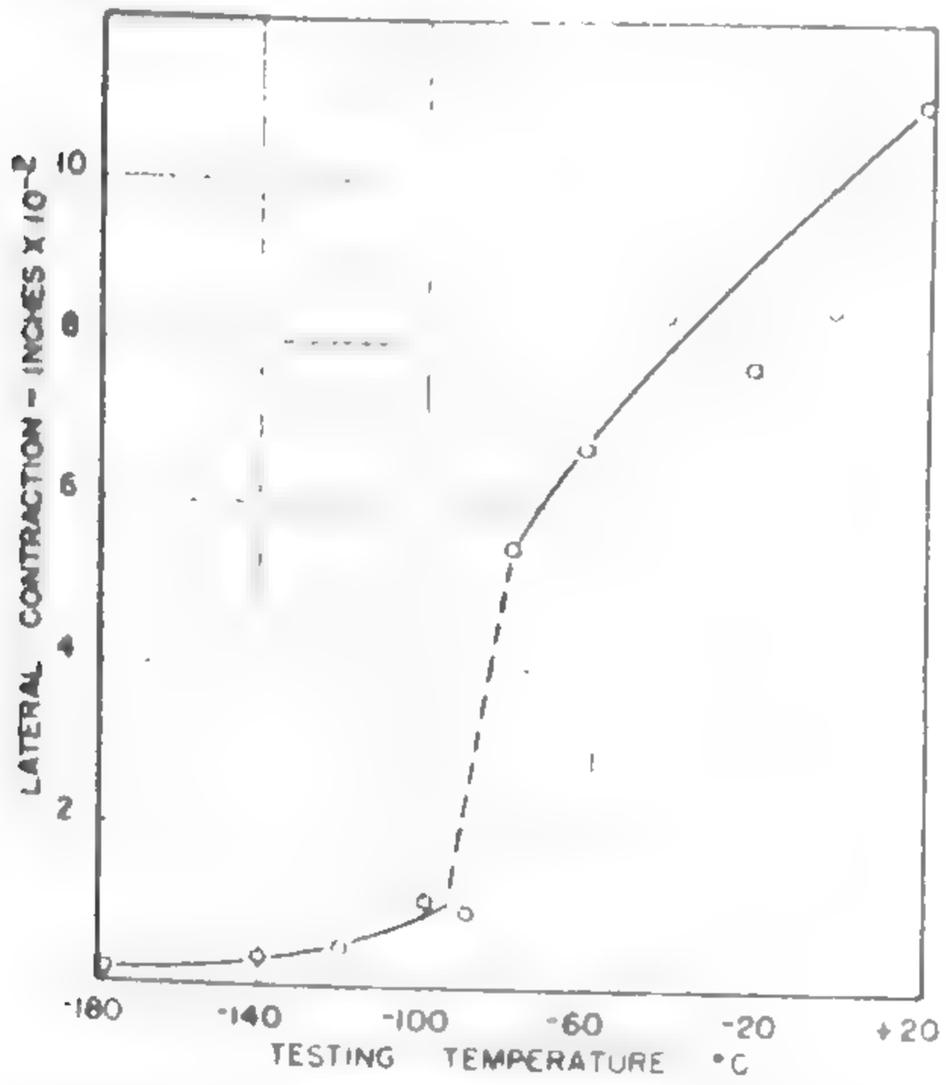
In general, the above-mentioned elements exert their influence on the microstructure and physical properties across the welded joint by:

1. Solid solution strengthening of ferrite.
2. Formation of carbides.
3. Formation of intermetallic compounds.
4. Oxidation or deoxidation of the melt.
5. Increasing or decreasing the hardenability of the heat-affected zone.
6. Grain size control.
7. Segregation phenomena.
8. Raising or lowering the transition temperature.

Certain of the above-mentioned nonmetallic elements are considered to contribute only detrimental characteristics to the properties of carbon and low-alloy steels. These elements are usually considered as impurities and will be described briefly as follows:

Nitrogen.—Open-hearth steels may con-

tain 0.0015 to 0.008% nitrogen, while Bessemer steels may contain as high as 0.030%. Nitrogen shows a tendency to form simple and complex nitrides with other alloying elements in steel; these nitrides may be partially responsible for strain-aging and embrittlement. However, plain carbon or low-alloy steels, containing greater amounts of nitrogen than mentioned above, are considered weldable if other conditions are correct. The strain-aging phenomenon in low-carbon steels is probably associated with and is attributable to the precipitation of nitrides on slip planes induced by straining and aging. The phenomenon is accompanied by increased hardness and loss in notch impact resistance and ductility. It is possible that cracking of base metal adjacent to the welds in some instances may be directly related to strain-aging. Some authorities have considered nitrogen as a factor in raising transition temperatures.



Note 0.03 in. lateral contraction equals 1%

Fig. 28.—Effect of Testing Temperature on Ductility Measured by Lateral Contraction for a 0.16% Carbon Semi-killed Steel

Hydrogen.—Although its solid solubility is extremely low both above and below the melting point of steel, hydrogen is absorbed during the making or welding of steel. The chief sources of hydrogen in the welding processes are the various types of atmospheres which surround the many different welding medias, electrode coatings containing moisture or cellulose compounds and the base metal itself. The presence of hydrogen in small percentages tends to make the arc erratic. Hydrogen is known to contribute to the formation of cooling cracks or *fisheyes* in welds. Many investigators attribute underbead cracking to the combined effect of hydrogen dissolved in retained austenite, as well as rate of heating and cooling, chemical composition and structure, and stress in the base metal. At least one authority has shown that little or no relation exists between the hydrogen content and transition behavior.

Sulfur.—Sulfur is usually kept below 0.05% in most steel specifications. With sufficient manganese to form MnS and with uniform distribution, little difficulty is encountered in welding steels due to sulfur content. With aggravated segregation, difficulty due to the melting-out of the complex sulfide inclusion from the plate at the fusion line can be encountered both with shielded-arc metal and submerged arc welding. Such behavior is often accompanied by cracks in the weld metal. The welding of steels containing 0.10% sulfur or more for free-machining characteristics is often troublesome. The employment of lime-type coated electrodes has been useful in welding steels of this class.

Phosphorus.—The most general source of phosphorus in steel is from the ore. Phosphorus is usually kept below 0.04% in most steel specifications. As little as 0.05% results in a noticeable increase in yield strength and a corresponding decrease in ductility. Phosphorus tends to segregate readily. It diffuses too slowly to permit homogenization in normal heat-treating or welding procedures, and thus may cause harmful banding, along with a harmful diffusion of carbon away from high-phosphorus areas. Nevertheless, excellent welding results have been obtained with low-carbon and low-alloy steels containing as much as 0.17% phosphorus.

Oxygen.—The solubility of oxygen in steel in the melting or welding process is about 0.2% when above the melting point of the metal, and about 0.1% when below. Oxygen exhibits a great tendency to form carbon monoxide (CO) on cooling and thus may form gas pockets in welds unless excess oxygen is converted to oxides by deoxidizers such as manganese, silicon, aluminum, titanium or vanadium. Oxygen as nonmetallic oxides of iron,

manganese, aluminum and silicon in the form of complex silicate slags is often present, and in the usual quantities does not cause difficulties in welding. While it is difficult to definitely point to oxygen in the base metal or weld metal as detrimental, it appears that its effect will depend chiefly on the metal with which it is combined, and the size and distribution of oxides formed.

The following elements, which are to be discussed, are those added as alloying additions to steel to perform some specific metallurgical or welding function:

Carbon.—Carbon is considered one of the most important limiting factors in welding. In oxy-acetylene welding, increased carbon is accompanied by increased ejection of sparks (commonly referred to as *sparking*) and boiling or foaming unless sufficient manganese and silicon are present to quiet this action. Carbon in the base metal exhibits no such action in arc welding, but its ability to harden the weld metal and base metal becomes a definite limiting factor when present, due to its deleterious effect on ductility. Welding of steels containing carbon in greater amounts than 0.30% usually involves the use of special welding techniques (preheat and postheat) in order to obtain sound welds with the required mechanical properties. In steels welded in the as-rolled condition, the transition temperature is raised as the carbon content increases.

Manganese.—Manganese is added to practically all steels for deoxidation purposes and to combine with sulfur to prevent hot-shortness. For this purpose there should be about eight times as much manganese as sulfur. Even small amounts of manganese greatly increase the hardenability in steels with over 0.20% carbon.

Increased manganese content results in increased sparking during welding in the absence of silicon. The sparking is attended by an infusible slag formation in oxy-acetylene welding, and a considerable amount of manganese is lost by volatilization and oxidation. These effects of high- or low-manganese contents are not manifest during arc-welding operations. However, increasing amounts of manganese will tend to make the slags formed during arc welding more fluid. Manganese, in the amounts usually occurring in commercial plain carbon steels (0.30 to 0.80%), imposes no limitations when the carbon content does not exceed 0.30%. Increasing carbon and manganese contents result in martensite formation, with a loss in ductility and an increase in hardness in the heat-affected zone. Manganese, in amounts up to 1.35% in the presence of 0.15% carbon or less, produces high-tensile strengths with little sacrifice in arc-welded performance. For improved transition behavior, the British have suggested that the manganese be maintained above three times the carbon content.

Silicon.—The addition of silicon (0.15 to 0.35%) to steels prevents the formation of CO and results in a so-called *killed steel.* Silicon, in the amounts usually occurring in steels for welding applications, is a benefit for all arc and gas welding processes. It is considered good practice to have the manganese content at least twice the silicon content, in order to insure fusible slags, particularly in forge or hammer welding operations.

Silicon is beneficial in gas welding since it promotes the reduction of iron oxide and thus suppresses the formation of gas by the reaction of oxides with carbon. Its oxidation product, silica, combines with any iron or manganese oxides to form easily fusible slags. The presence of silicon suppresses sparking. Steels containing up to 1.00% silicon have been welded successfully, the silicon content producing no detrimental action during the welding operation. The tendency for porosity is dependent upon the relative manganese and silicon contents and may be avoided by specification of a minimum manganese content of 1.00% and a maximum silicon content of 0.40% for gas welding rods.

Chromium.—Chromium, in the amounts ordinarily used in engineering steels, exerts no detrimental action during welding by either the gas or arc processes. Sound welds can be made in steels containing up to 30% chromium. Chromium is quite susceptible to oxidation, and increases hardenability; however, by adopting correct welding procedures, no trouble due to chromium should be experienced. The amount of chromium added must be balanced with the carbon content. An increase in chromium content should be accompanied by a decrease in carbon in order to prevent air-hardening characteristics.

Molybdenum.—Molybdenum is usually

employed in conjunction with manganese or chromium, and steels containing this element are easily welded by the gas- and arc-welding processes. Molybdenum has no slag-forming characteristics and its presence is not noted during the welding operation. No serious difficulties have been encountered in welding heavy plate structures of steels containing 0.5% molybdenum if the carbon content is kept below 0.15% even though molybdenum has a very great effect on the hardenability of the base metal.

Nickel.—Steels containing nickel melt quietly in the oxy-acetylene process and offer no difficulty with either the gas or arc welding processes when suitable rods and electrodes are used. Nickel contributes only mildly to hardenability, hence, it is useful in compositions intended to be insensitive to the rapid cooling in welding processes.

Copper.—Copper, in amounts up to 1.0%, does not affect the welding operation so far as the making of the weld is concerned. Weld cracking difficulties have been attributed to copper, but this depends on the process used and the remaining composition of the steel.

Vanadium.—Vanadium is used in such small amounts in carbon and low-alloy steels that its presence is not usually recognized during the welding operation. However, its presence, when dissolved in the base metal in small amounts (0.04%), increases hardenability slightly and restrains grain growth. Vanadium in the range from 0.05 to 0.15% acts as a toughening agent and decreases the notch sensitivity of mild steel.

Aluminum.—Aluminum is ordinarily used as a deoxidizer and grain-refining element. Properly refined steels that have been aluminum-treated with up to 3 lb. per ton exhibit no adverse effects during fusion, though such steels may often contain residual aluminum or aluminum oxide. If too large an amount of aluminum has been used for the above operations, an infusible scum appears in the welding operation that prevents a free flowing weld, and usually results in porosity. This is particularly noticeable in light-gage metal such as rim or barrel stock. Defective welds in both gas and resistance welding have been traced to aluminum and alumina in steel. Apparently, steels containing up to 0.2% aluminum can be arc-welded satisfactorily when mineral-coated electrodes are used, and there is usually no trouble encountered with cellulose-coated rod when properly used with high current.

Titanium.—Titanium appears to have no effect on the welding operation in the amounts present in carbon and low-alloy steels. It is usually employed as a cleaning agent or carbide former. A considerable amount of titanium is lost by oxidation in the fusion of the metal unless a sufficient quantity is added by a special technique.

Zirconium.—Zirconium is usually added to steel in the ladle, where it has a strong deoxidizing action and acts as a scavenger. It forms a fusible slag which tends to rise out of the metal and remove with it oxygen, nitrogen and nonmetallic inclusions. The presence of from 0.08 to 0.10% zirconium will usually result in a fine-grained steel. It has no apparent effect on welding and the low-alloy steels containing zirconium are weldable. It is worth while to note that vanadium, titanium and zirconium display a very similar action as alloying elements in steel.

Alloy Steels, Hardenable

General.—The influence of specifically added alloying elements to plain carbon steel is especially important if this steel is to be welded. Alloying elements not only affect the final products of the steel in the weld and base metal, but control the rate of austenite transformation in the heat-affected zone during and following welding. On cooling to room temperature, the nature of the transformation products determines the capacity of the steel to withstand the severe thermal stresses that are induced. A sufficiently soft and ductile metal structure can relax these stresses; strong and brittle microstructures, such as those of martensite, either retain the thermal stresses without plastic adaptation to these forces or release them by cracking and rupture.

Effect of Composition.—The most important effect of an alloying element is to change the transformation rates of austenite and thus to affect the hardening and tempering processes of the steel. The presence of an alloying element may modify the entire transformation curve of a carbon steel of a given carbon content. Figure 29 shows how the transformation curves of a 0.35% carbon steel are altered by the addition of 1.97% chromium to

the steel. It may be noted from this figure that while it would be almost impossible to prevent the partial transformation of the austenite on even drastic cooling of a plain carbon steel, it would be quite possible to do this after the addition of the alloying metal.

It is common to refer to this difference in rate of transformation by saying that the critical cooling rate at which the alloy steel will transform completely to martensite is lower than that for the plain carbon steel. Since by hardenability we mean the ability of a steel to form martensitic products on slower and slower rates of cooling, the alloy steel will have a higher hardenability than the carbon steel.

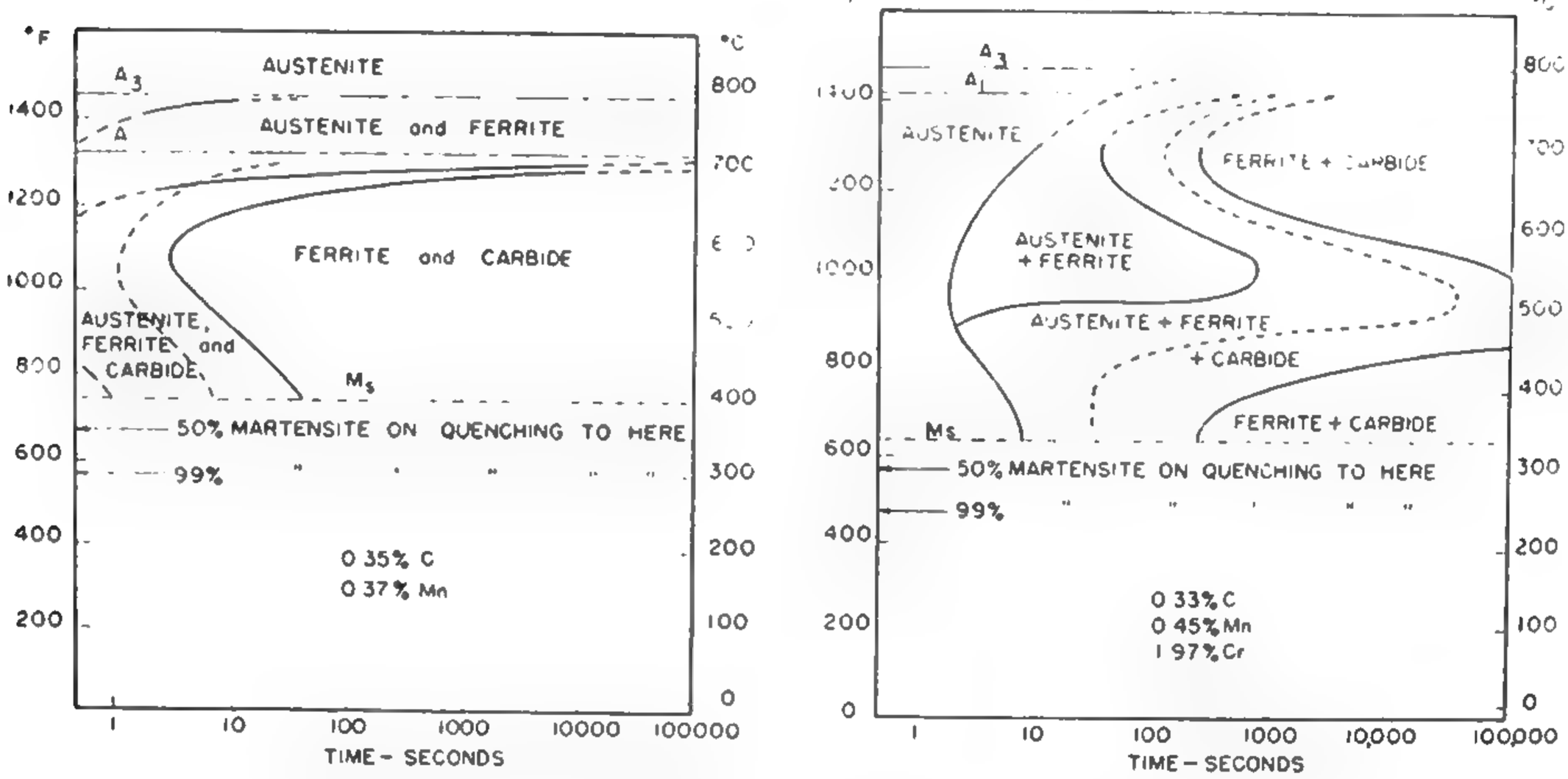


Fig. 29.—Modification of Transformation Diagram by Alloy Addition

The greater the hardenability, the more deeply it will be fully hardened. If a number of bars of any given steel, but of different diameters, are quenched, it will be found that there is a bar of critical size which will just be hardened throughout, and this limiting diameter may be used as a measure of hardenability.

If a steel is a very deep-hardening steel, it may be impractical to determine hardenability from bars of moderate diameter. In such cases it is necessary to use a long bar which is heated to the desired quenching temperature and then quenched in such a way that only one end face is in contact with the quenching medium. This test is called the *end-quench* or *Jominy* hardenability test. Hardness measurements are made along a flat cut at a fixed depth along the 4-in. length of the bar. In general, steels with high hardenability are more susceptible to hardening and cracking during the welding operation, hence require the use of preheat or postheat in order to decrease the rate of cooling and prevent the formation of hard martensite.

One of the effects of alloying elements in hardened steel containing carbon consists in hardening the ferrite phase by solid-solution hardening. The full importance of these added alloying elements is indicated in their modification of the iron-carbon diagram. The most significant of these modifications is the ability of some elements to change a temperature range, over which either austenite or ferrite can exist in stable form.

In addition to actual solution in the austenite phase, the alloying elements will combine themselves with the carbon present in the steel, and the relative amounts present in carbide or in solution will depend entirely on the carbide-forming tendency of the alloying element. In some cases, this may be high and all of the alloying element will be present in the form of complex carbides, which may be difficult or impossible to get into austenite solution. It may be expected in such cases that the hardenability of such a steel will be considerably affected due to the lack of perceptible carbon. Fundamentally, the temperature and composition range in which it is possible to obtain a

pure austenite solution will depend very much upon the material and amounts of alloying element present.

The alloying elements may be divided into two classes: (*a*) those which enlarge the austenite zone of iron-carbon alloys, and (*b*) those which restrict or otherwise cause it to vanish.

Nickel, cobalt and manganese are elements typical of the first group. Figure 30 shows the effect of various concentrations of manganese on the austenite zone.

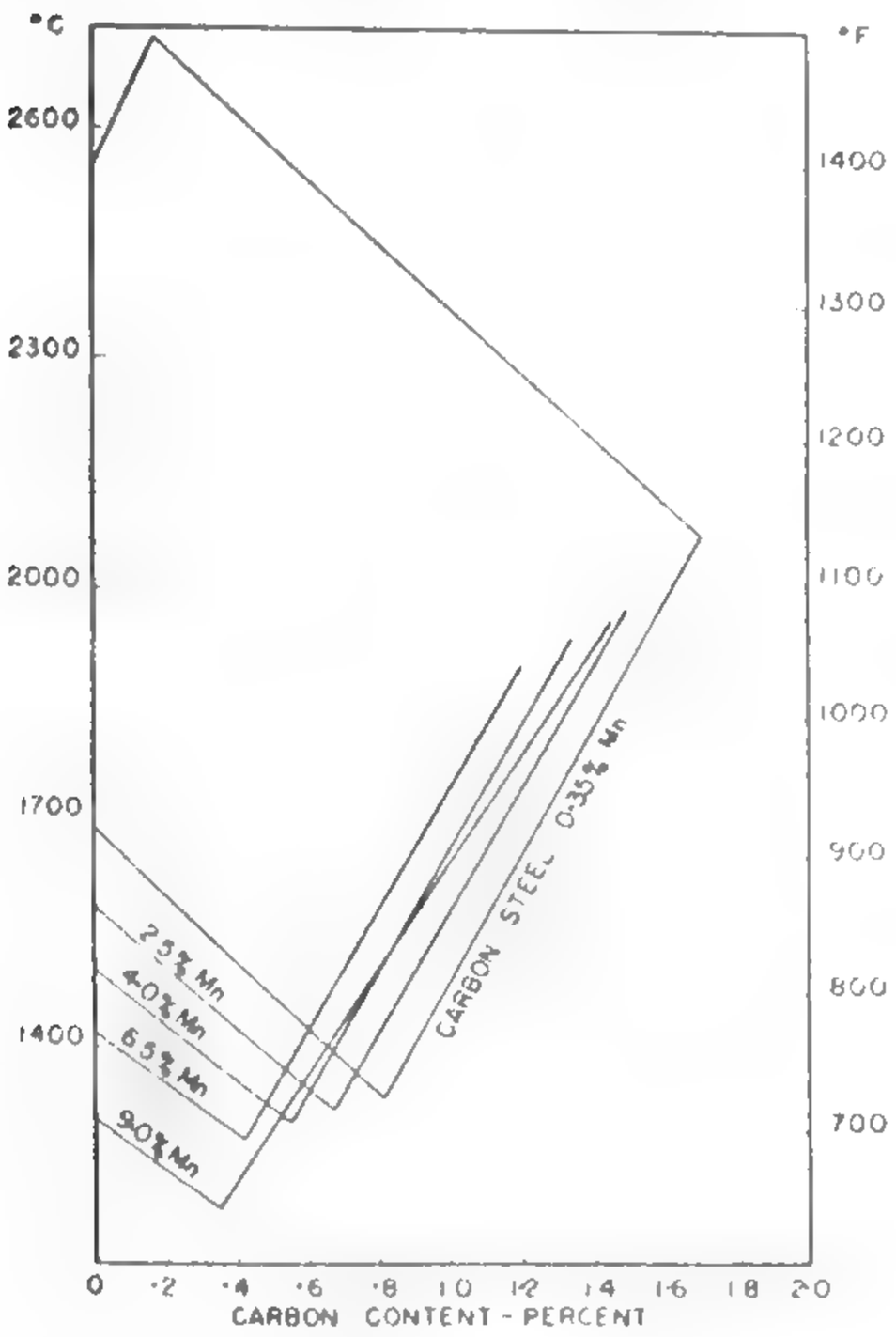


Fig. 30.—Effect of Manganese Content on the Austenite Zone

The effects of cobalt and nickel are quite similar. It may be noted that as the manganese content is increased, both the eutectoid temperature and the composition are progressively shifted to the left and down. Figure 31 shows the effect of increasing amounts of silicon on the austenite zone. Table 1 lists some of the general effects of alloying elements in steel.

Application of Isothermal Diagrams to Welding

In welding, the base metal adjacent to the weld deposit is heated to a temperature high enough to transform it to austenite. If the heat-affected zone in alloy steels is allowed to cool normally, the austenite will decompose more or less completely to martensite. However, if the cooling in the heat-affected zone is delayed with a postheat treatment, the austenite will decompose to intermediate structures, depending on the temperatures to which the metal is cooled after welding, the time it remains at this temperature and the rapidity of cooling to that temperature. To insure adequate ductility in the metal adjacent to the weld, it is

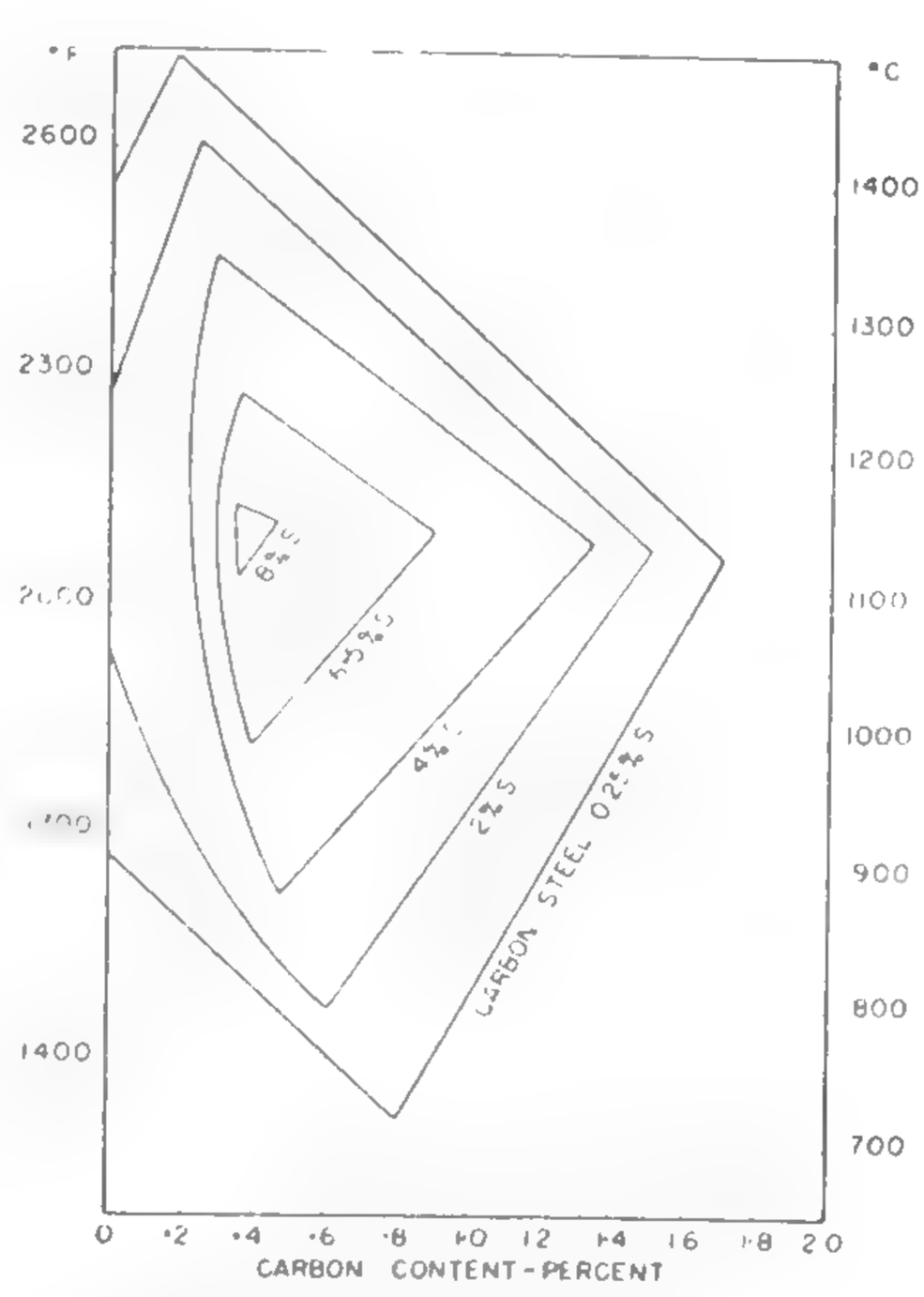


Fig. 31.—Effect of Silicon Content on the Austenite Zone

important to consider its metallurgical behavior as it cools after welding.

The tremendous difference in time for transformation, as it depends upon the reaction temperature, may be seen by examining the isothermal curves of a material such as SAE 4340 (Fig. 32). Improved ductility is to be expected only when the transformation of austenite is completed at some elevated temperature. The use of postheat, of sufficient duration to permit complete transformation at the postheat temperature of the austenite formed during the welding operation, results in improved ductility of the heat-affected zone. Suitable postheat technique often makes possible the establishment of a shorter welding cycle by developing the

properties of a normalized material without heat treating entire assemblies after welding.

Indications have been found that time and temperature of postheat for optimum ductility are related to the isothermal transformation characteristics of the steel used. The isothermal diagram may be used as a guide in the selection of postheat temperature and time. Preheat is important only as far as it affects postheat conditions. Since the maximum ductility of steel follows closely its complete isothermal transformation, the isothermal transformation curve can be used as a first approximation in determining the proper postheat temperature and time.

Table 1—Effects of Some Alloying Elements in Steel

Stabilization of Austenite	Hardening Tendency on Transformation	Carbide Formation	Restriction of Grain Growth	Stabilization of Ferrite	Strengthening of Ferrite
Nickel	Carbon	Vanadium	Aluminum	Chromium	Manganese
Manganese	Molybdenum	Titanium	Vanadium	Molybdenum	Silicon
Nitrogen	Chromium	Columbium	Titanium	Phosphorus	Phosphorus
Carbon	Manganese	Tantalum	Zirconium	Tungsten	Cobalt
Copper	Nickel	Tungsten	Nitrogen	Vanadium	Nickel
	Tungsten	Molybdenum		Silicon	Aluminum
	Vanadium	Chromium		Aluminum	Chromium
		Manganese		Titanium	Molybdenum
				Zirconium	Tungsten
					Nitrogen
					Copper
					Vanadium
					Oxygen

The possibility of extending the principle of controlled postheat to the welding of steels of many compositions may be realized from the examination of the portions of isothermal transformations reproduced in Fig. 32. The ductility and soundness of the heat-affected zone in most of the medium-carbon alloy steels may be improved by selecting suitable postheat temperatures and time in order to ensure complete transformation of the hardened structures in the heat-affected zone.

Stainless Steels

General.—There are over two dozen varieties of stainless steels which are generally characterized by their improved resistance to corrosion and oxidation. All varieties of stainless steels are welded under commercial conditions; however, the welding techniques for different types vary quite widely. The austenitic group of stainless steels, containing both chromium and nickel, is more readily and satisfactorily welded than the group which contains only chromium. Since the response to welding is not the same for the two groups, they will be discussed separately. (See Chapter 31 for further information on the welding of stainless steels.)

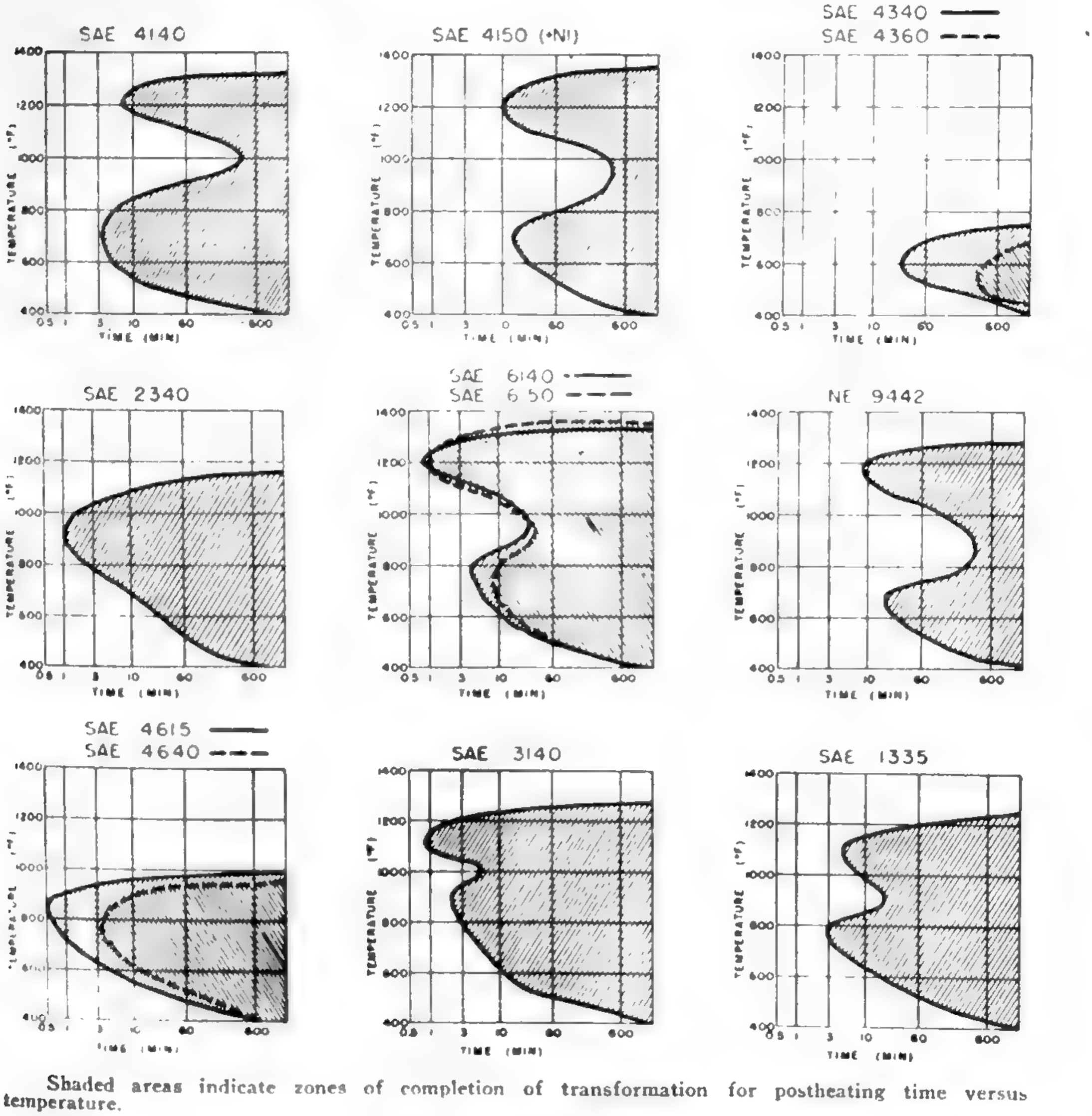
Austenitic Steels.—Austenitic alloys, containing both chromium and nickel, and characterized by their excellent resistance to corrosion and oxidation, have important applications in welded construction, both as base material and as added weld metal. Carbon in iron is very effective in forming austenite, but its limited solubility makes it necessary to add chromium, nickel or manganese for full-phase stabilization. Nitrogen may be used to replace nickel or carbon in some applications. Only sufficient alloying elements are added to austenitic steels to make the material stable under the expected conditions of service.

When utilized at room temperatures, the kinetic energy in the austenitic steel is sufficiently low to prevent transformation, even over an indefinitely long period of time. At certain elevated temperatures, in excess of 750°F. (400°C.), however, and over long exposures, some decomposition may occur, especially if the steel contains elements such as chromium, molybdenum or silicon, improperly balanced in respect to other elements of its composition.

In the corrosion and heat-resisting steels, alloys of 18% chromium–8% nickel with molybdenum; 20% chromium–10% nickel; 25% chromium–12% nickel; and 25% chromium–20% nickel, may be

regarded as modifications of the general type having the well known 18% chromium–8% nickel composition. They are particularly stable for temperatures ranging from a low temperature such as encountered in liquid oxygen (—297.4°F. or —183°C.) to a higher temperature of work. As the temperatures approach 1900°F. (1038°C.), solution of the carbides occurs and may be complete on holding at this level.

Elements such as columbium, titanium and vanadium, which are carbide-forming, are also ferrite-stabilizing. Where they



Shaded areas indicate zones of completion of transformation for postheating time versus temperature.

Fig. 32.—Isothermal Curves

approximately 900°F. (482°C). Even a short time at the temperature range of about 900 to 1400°F. (482 to 760°C.) may result in intergranular precipitation of carbides. At still higher temperatures, the precipitation is less selective and can occur within the grain. At lower temperatures, precipitation may occur along shear planes produced by mechanical form highly stable carbides not easily soluble in austenite, even at high temperatures, they tie up some of the carbon and prevent its contribution to the austenite formation. Their carbides are slow to diffuse, coalesce or dissolve in the austenitic solid solution.

The grain boundary carbide precipitation at 900 to 1400°F. (482 to 760°C.)

is undesirable because it permits a localization of corrosive attack and consequent embrittlement in media normally not severely corrosive to steels of the 18–8 or more highly alloyed types. Weldable steels of the 18–8 type are limited by specification to a maximum of 0.08% carbon* in order to minimize intergranular carbide precipitation from the welding heat. The time dwell within the susceptible temperature range will vary with the means, technique and extent of welding, as well as the thickness of the members to be joined. Titanium and columbium added to the 18–8 base metal have the advantage of eliminating sensitivity to intergranular precipitation. Their useful contents are usually four to ten times that of carbon. Titanium is too easily oxidized during welding for effective transfer through the welding zone. Columbium does not have this objection and is employed almost universally for this purpose. The addition of columbium to form columbium carbides can restrict intergranular localization by its previous precipitation within the grains and by allowing only sluggish diffusion toward the grain boundaries.

Exposure to 1600°F. (871°C.) and below, with compositions of lower carbon and higher chromium, nickel, silicon, molybdenum or other elements than the 18–8 type, may permit the formation of a brittle sigma phase. This forms with an approximate composition, as the intermetallic compound FeCr. Such changes in the austenitic alloy are significant in prolonged high-temperature service and even during the shorter time periods of welding heat exposure. A properly balanced composition is consequently necessary to prevent the formation of the sigma phase.

High-Chromium Steels.—From the standpoint of welding, the straight chromium stainless steels can be grouped into two classes: those containing up to 14% chromium which harden intensely if allowed to cool rapidly in air from high temperatures; and those with 18 to 30% chromium which do not harden when cooled rapidly. The intermediate steels containing 14 to 18% chromium behave in a manner that depends upon their exact chromium and carbon contents.

*In order to meet this requirement, production specifications often aim for a maximum of 0.06% carbon.

The high-chromium steels, those containing above about 20% chromium, are characterized by somewhat greater brittleness than is shown by the lower-chromium alloys in their fully-annealed, dead-soft condition. The tendency for grain growth with increased brittleness results if these alloys are held at over 1650°F. (900°C.). If held at around 1200°F. (649°C.) or if cooled slowly through this range, brittleness may result. In order to avoid large grain growth during welding, care is taken to avoid high concentrations of heat of long duration. The use of small weld beads to avoid unnecessary heat build-up is helpful. For best corrosion properties, full annealing after welding is recommended.

NICKEL AND HIGH-NICKEL ALLOYS

General

The ensuing discussion applies to nickel-base alloys containing more than 50% nickel, and, for convenience of treatment, is further confined to three types of alloys which are in wide use and commonly fabricated by welding. (See Chapter 35 for further information on the welding of these materials.) The three classifications are as follows:

(*a*) Nickel
(*b*) 70 Nickel-30 Copper (Monel)
(*c*) 77 Nickel–15 Chromium–8 Iron (Inconel)

Nickel-Base Metal

The most commonly used grade of commercial rolled nickel contains about 0.04–0.07% carbon, which is satisfactory for most applications from approximately 700°F. (371°C.) down to very low temperatures. However, under service conditions involving long-time exposures at temperatures of the order of 700°F. (371°C.) or higher (such as in fused caustic applications), nickel may in time become embrittled immediately adjacent to the weld. This area has, in effect, been quenched from a high temperature during welding, and when the weldment is subsequently placed in service under the conditions indicated above, the carbon is rejected as intergranular graphite. This graphitization is avoided by using a low-carbon variety of nickel, commercially designated *L* nickel, for weldments in-

tended for such service. Due to its low-carbon content, *L* nickel possesses somewhat lower strength properties than commercial nickel, which may occasionally be a factor to be considered from a design angle.

70 Nickel–30 Copper (Monel)

The heat-affected zone of Monel weldments is quite free of graphitic embrittlement tendencies, and no special grade of Monel is needed for elevated temperature service. The relative insensitivity to embrittlement of the nickel-copper alloy, compared to nickel, is due in large part to the lower solubility of carbon in Monel.

77 Nickel–15 Chromium–8 Iron (Inconel)

As in the other alloys, no difficulties are encountered in the heat-affected zone, from a weldability standpoint. For most applications, therefore, neither preheat nor postheat is required. However, under conditions involving exposure to certain corrosive media at high temperatures, a postheat treatment may be desirable to dissolve intergranular carbides rejected in the heat-affected zone.

Weld Metal

In welding the high-nickel alloys, great care must be exercised to avoid contamination of the fusion zone with such deleterious elements as lead, sulphur, bismuth, etc. The principal sources of such contamination are found in improper cleaning and preparation of the material to be welded, and the use of flux or electrode coating ingredients containing excessive amounts of such elements as impurities. Excessive amounts of boron are also undesirable and usually enter the weld metal through the use of high-boron-content fluxes, especially in gas welding

Lead.—This element, even when present in very small amounts, reduces weld hot-ductility sharply, causing hot-cracking either during welding or on reheating for stress-relief or in subsequent elevated temperature service. Other so-called *heavy metals* such as bismuth are also troublesome.

Sulphur.—Unless properly fixed by suitable elements such as magnesium, sulphur will form, with nickel, a nickel-nickel sulfide eutectic, molten at about 1200°F. (649°C.), which will make the material hot-short and produce cracked welds. While sufficient residual sulfur-fixing elements are present in the sheet and wire to take care of the normal amounts of sulfur, they cannot prevent excessive contamination of the weld metal by sulfur from such external sources as flux ingredients, improperly cleaned surfaces, etc. In some instances, high-sulfur content welding slags can also produce surface embrittlement of the sheet adjacent to the weld to a damaging extent, particularly in welding light-gage material.

Boron.—Compounds of boron are quite readily reduced in both gas and arc welding, thus introducing boron into the weld metal. While the nickel alloys possess a small tolerance for boron, the excessive weld contamination produced through the use of fluxes containing large amounts of boron compounds may result in brittle and cracked welds.

Carbon.—In gas welding nickel-base alloys, a neutral or very slightly reducing flame is recommended. Considerable amounts of carbon can be introduced into the weld metal by using a strongly reducing flame. Such high-carbon welds are susceptible to corrosion or embrittlement or both, and carbon pickup during welding should, therefore, be avoided.

The use of L nickel in applications involving long-time exposures at temperatures above about 700°F. (371°C.) in order to avoid embrittlement in the heat-affected zone, has been discussed. It should also be recognized that the weld metal must likewise be resistant to graphitic embrittlement. This may be accomplished by depositing weld metal low in carbon or by adding carbon-stabilizing elements to the core wire or flux coating, so that the weld metal will be structurally unaffected in subsequent service. Electrodes are available which function on the latter basis.

Gases.—The molten nickel-base alloys dissolve considerable amounts of nitrogen and hydrogen, which are released during solidification, producing weld porosity. Care should be taken to avoid sources of hydrogen in welding fluxes, both by choice of flux composition and by adequate drying of coated electrodes. Nitrogen is always present in the arc and its effects are best neutralized by the addition of suitable nitrogen-fixing elements to the core wire or to the flux.

Silicon.—In the case of alloys of the

Inconel type, some care must be taken to control weld composition with respect to silicon in order to prevent hot-cracking. It has been found that the presence of silicon in Inconel weld metal in amounts greater than about 0.35% may be accompanied by hot-cracking, the tendency increasing with the silicon content. Columbium, if present in the weld metal in sufficient amounts to insure a columbium-silicon ratio of about 4.5 : 1, probably neutralizes the complex silicon effect and permits production of welds which are substantially free of weld hot-cracking tendencies. Electrodes are commercially available which deposit compositions suitably resistant to hot-cracking.

Age-Hardenable Nickel Alloys.—There are a number of age-hardenable alloys such as K-Monel, Inconel X, etc., which are occasionally fabricated by welding. The welding procedures are similar to those used for the corresponding conventional alloys. However, in order to obtain the maximum response to heat treatment of the deposited weld metal, it is desirable to purchase sheet which has already been partially heat treated so that it only requires a final aging treatment. Alternatively, the material may be *solution treated* before welding. After welding, it is then only necessary to apply the recommended aging treatment. This procedure not only minimizes distortion, but also results in a better response to aging in the weld metal than would be obtainable if the weldment were given a full heat treatment after welding.

Summary

This discussion attempts to present a broad picture of the welding metallurgy of nickel-base alloys. The absence of transformations usually makes preheating and postheating unnecessary and eliminates such difficulties as hard and brittle areas adjacent to the weld, underbead cracking, etc., which are encountered in the welding of some steels. The welding problems in nickel-base alloys are generally related to the deposited metal rather than to the heat-affected zone, and hence to contamination of the deposit with deleterious elements.

In making a broad classification of nickel alloys, it has not been feasible to deal with several alloys such as the Hastelloys and others, which have important industrial uses. Some information on these materials will be found in Chapter 35.

COPPER AND COPPER ALLOYS

General

The following section on the metallurgy of copper and the copper alloys deals only with those properties of the materials which are involved in welding, brazing and soldering operations. However, since beneficial or ill effects in heat-joining operations are often determined by the alloying element itself, it is necessary to discuss such alloying agents one by one. Furthermore, metallurgical effects are many times occasioned by the ambient atmosphere or welding gases and heating methods. These features are therefore discussed.

With respect to the formation of alloys, copper is a rather versatile element, more than one-third of the ninety-six known elements being involved in the manufacture of the copper alloys. Copper serves as the base element for more than one hundred common commercial alloys: brasses, bronzes, cupro-nickels, nickel silvers, copper-silicon alloys, leaded brasses and bronzes, etc., which have a wide variety of useful applications.

Welding procedures are given in Chapter 34, and additional information on the general metallurgy and metallurgical properties of the copper alloys will be found in the bibliographic references at the end of this chapter.

Major Alloying Elements

Fourteen elements are associated with copper to make several hundred copper alloys sold under a thousand different names. These additions usually result in a metal having a single metallurgical constituent—the alpha phase—which unlike steel does not change phase or chemical composition when melted and solidified, when heated and cooled, however fast the cooling is performed. See Figs. 2, 3 and 5.

Some copper alloys, however, have more than one metallurgical phase and at least three are heat-hardenable. With such alloys, heating and cooling effects must be considered; these will be considered later.

The fourteen major alloying elements of copper are listed in Table 2 together with the names of the resulting alloy.

The atomic number and weight are shown because more and more attention is given to these properties in metallurgy as well as in chemistry.

The density figure gives a convenient means of computing weights from known volumes or vice versa. The values for the elements cannot, however, be used in direct proportion to compute the density of the resulting copper alloy. The densities of the copper alloys vary only from an approximate minimum of 0.274 for aluminum bronze to a maximum of 0.323 lb. per cu. in. for pure copper, whereas the densities of the elements vary from the value of 0.0657 for phosphorus to 0.409 lb. per cu. in. for lead.

Copper.—Pure copper, free of oxides and other impurities is characterized by good hot and cold workability. It has a good average strength in the cast or annealed condition of 30,000 to 35,000 psi., which can be approximately doubled by cold-rolling or cold-drawing. It has the highest electrical conductivity and thermal conductivity of any of the commercial metals.

The electrical and thermal conductivities are reduced by alloying additions. The amount of the reduction of the electrical conductivity depends upon the alloying agent and the amount used. Most other properties as strength, weldability, hardness, durability, etc., can be improved

Table 2 Properties of the Major Alloying Elements Used with Copper

Element	Atomic No.	Atomic Weight	Density, Lb. per Cu. In. at 68°F.	M. P. °F (°C.)	B. P. °F (°C.)	Generic Name of Alloy with Copper
Aluminum	13	26.97	0.0975	1218 (659)	3273 (1800)	Aluminum Bronze
Arsenic	33	74.93	0.2070	1139 (615)	Sublimes	Arsenical Copper
Beryllium	4	9.02	0.0658	2435 (1285)	5040 (2782)	Beryllium Copper
Cadmium	48	112.41	0.3152	610 (321)	1413 (767)	Copper-Cadmium Bronze
Chromium	24	52.01	0.2579	3350 (1843)	4500 (2482)	Chromium Copper
Copper	29	63.57	0.323	1981 (1083)	4700 (2315)	Copper[a]
Iron	26	55.84	0.284	2795 (1535)	5430 (3000)	No binary alloy in copper
Lead	82	207.20	0.409	621 (327)	3170 (1743)	Leaded Copper, Brass, Bronze
Manganese	25	54.93	0.268	2268 (1242)	3905 (2152)	Manganin, Manganese Bronze
Nickel	28	58.69	0.322	2646 (1452)	5252 (2900)	Cupro-nickels. Nickel silvers. Constantan
Phosphorus	15	31.02	0.0657	Ignites 90		Phos-Copper, Phosphor Bronze, Phosphorus deoxidized Copper
Silicon	14	28.06	0.087	2588 (1420)	4712 (2600)	Copper-silicon alloy, Everdur, Herculoy, etc
Silver	47	107.88	0.380	1761 (961)	3635 (2002)	Silver-bearing Copper, Silver Brazing Alloys
Tin	50	118.70	0.264	450 (232)	4118 (2270)	Bronze, Phosphor Bronze
Zinc	30	65.38	0.258	786 (419)	1665 (907)	Brass, Special Bronzes, Nickel Silvers

[a] Elementary copper. Commercial coppers with fractional percentages of other elements are known by various names as Tough-Pitch Copper, Electrolytic Copper, Deoxidized Copper, Oxygen Free Copper, High-Conductivity Copper, Arsenical Copper, Silver-Bearing Copper, Lake Copper, etc.

The melting temperature is an important index in arc and gas welding and brazing. The boiling temperature is important in only three cases, i.e., alloys with phosphorus, zinc and cadmium. This effect is discussed under the element in question.

These elements are added to copper, one or several at a time to form alloys valued for their physical, corrosion-resisting and aesthetic properties.

by suitable additions as indicated below.

Oxygen-Bearing and Deoxidized copper.—Most of the electrical copper and general-purpose copper in wire, bars and sheets is of the oxygen-bearing, tough pitch variety carrying 0.03 to 0.07% oxygen in the form of minute specks of cuprous oxide-copper eutectic. This electrical and general purpose, tough-pitch copper is readily soft soldered, silver brazed and flash-welded but should not

be used where the copper is to be arc or gas welded. Deoxidized copper should be used in the latter case.

Minor Additions to Copper and Copper Alloys

In this group eighteen elements may be mentioned: antimony, barium, bismuth, boron, calcium, carbon, cobalt, gold, lithium, magnesium, mercury, sodium, titanium, vanadium, tungsten, selenium, sulfur and tellurium.

Of these eighteen minor elements, only a few are used at this time in commercial copper alloys. For copper alloys joined by welding, the use of these minor elements is even more restricted.

Boron, calcium, magnesium, lithium and/or sodium may be employed in copper as deoxidizers but little, if any, is left in the resulting alloy. They would rarely be encountered in welding metallurgy. Antimony has been used to some extent to raise the annealing point of copper but in amounts so small as to have practically no influence on welding operations. Powdered copper, tungsten and/or cobalt are pressed and sintered to make resistance spot-welding electrodes. Carbon is practically insoluble in copper alloys, the high-nickel cupro-nickels being excepted. Hence, carbon is not the important reagent in copper that it is in iron. It is regarded as an undesirable impurity in the cupro-nickels, and it is rarely encountered therein. Selenium or tellurium may be used to improve machinability of cold-drawn electrical copper. Lead is used for the same purpose. Sulfur is important in the extractive metallurgy of copper. However, it is rigidly excluded, by suitable refining processes, from commercial copper and copper alloys. Hence, it is not encountered in the welding of copper alloys. Gold alloyed with copper in art objects and jewelry is gas welded without difficulty or metallurgical complications. Mercury is rarely, if ever, involved in the welding metallurgy of copper.

Effects of Welding and Ambient Gases

Fuel gases and gasified liquids as acetylene, methane and other carbon-hydrogen gases and liquids, alcohols, etc., break down and react when ignited in the presence of oxygen or air, into (1) hydrogen, (2) water vapor, (3) carbon monoxide and (4) carbon dioxide. Hence, these new gases are the ones which react with the metals rather than the original fuel gas and are the ones to be considered. These gases may be divided into three groups depending upon their action on the cold or hot metal: (1) oxidizing, (2) reducing and/or (3) neutral or shielding action as shown in Table 3.

A fourth action which has an important part in the soundness or lack of soundness in a weld is the relative solubility of a gas in the molten metal and the solid metal. Little information is avail-

Table 3—Effect of Ambient Gases on Welding of Copper Alloys

Name of Gas	Formula	Typical Reaction with Copper Alloy Metal at Brazing or Welding Temperatures
Oxidizing Gases:		
Oxygen	O_2	Forms oxides with copper and copper alloying elements, the reaction being more active as the temperature of the metal or the concentration of the oxygen is increased.
Water vapor	H_2O	Neutral to cold metal, oxidizing to some hot metals. The oxidizing action is important only in the case of the beryllium, chromium, aluminum and silicon-copper alloys.
Carbon Dioxide	CO_2	Action is generally neutral but may be oxidizing to aluminum, beryllium and chromium at elevated temperatures.
Reducing Gases:		
Hydrogen	H and H_2	Hydrogen gas, or hydrogen from acetylene or other hydrogen-carbon fuels, causes the *hydrogen embrittlement* of tough-pitch copper at temperatures above red heat.
Carbon Monoxide	CO	Carbon monoxide is only mildly reducing.
Neutral Gases:		
Nitrogen	N_2	Not so satisfactory as helium or argon as an inert shield in arc welding. However, it forms no brittle compounds of copper similar to iron nitride. It does not interfere appreciably with gas or arc welding.
Helium	He	Good inert shield in arc welding.
Argon	A	Good inert shield in arc welding.

able on these solubilities; moreover, the volume of a given gas dissolved in the molten metal depends upon the temperature of the molten weld metal and the area of contact. The unsoundness of the weld, i.e., volume of gas rejected by the solid metal, may also depend upon the rate of solidification.

a manufactured source is by far the most important gas with which a welding operator is concerned. At room temperatures or at an elevated temperature, it forms oxides, sometimes of several different formulas, for a given metal. The principal oxides of interest to the copper alloy metallurgist are given in Table 4.

Table 4—Oxides of Elements Used with Copper

Element*	Principal Oxide	Oxide Melts, °F. (°C.)	Oxide Boils, °F. (°C.)	Nature of Oxide on Weld Melt
Aluminum	Al_2O_3	3722 (2050)	4082 (2250)	Tough, refractory. Floats but is apt to be folded in. Difficult to flux.
Arsenic	As_2O_3	379[a] (193)	Subl.	No interference in welding.
Beryllium	BeO	4658 (2570)	7100 ± (3930 ±)	Tough, refractory. Floats but is apt to be folded in. Difficult to flux.
Cadmium	Cd_2O	1652[b]	...	No serious interference but high density, 8.2, may cause the suboxide to be entrapped in the metal.
	CdO	(900)		
Chromium	Cr_2O_3	3614 (1990)	Very high	Refractory, brittle, hard. Difficult to flux.
Copper	Cu_2O	2255 (1235)	3272[c] (1800)	Easily reduced, easily fluxed. Cu_2O dissolved in melt but is rejected as metal solidifies as microscopically small particles scattered throughout the metal
	CuO	1879[b] (1026)	.	
Iron	FeO	2588 (1420)		Easily fluxed, easily reduced with carbon monoxide. Not important in copper welds.
Lead	Pb_2O	[b]	.	Unstable. Causes porosity.
	PbO_2	554[b] (290)	...	Heavy, sinks in melt. Fluxible.
Manganese	MnO	3002 (1650)	....	Readily fluxed. High oxide, unstable.
Nickel	NiO to Ni_2O_3	752 (400)	.....	Tight, closely clinging refractory scale. Difficult to flux.
	Ni_3O_4	1112[b] (600)	.....	
Phosphorus	P_4O_6	75 (24)	338 (170)	Acts as deoxidizer, flux like
	P_2O_5	1045 (563)	650[b] (347)	
Silicon	SiO_2	3115 (1713)	4046+ (2230)	Element is a strong deoxidizer. Oxide combines with other metal oxides to form glass melting at 1600°F ± to form continuous impervious flux-like film on the weld pool.
Silver	Ag_2O	572 [b] (300)	.....	No interference, sublimes.
Tin	SnO	1292 1742[b] (700 950)	....	Easily fluxed, easily reduced with phosphorus
	SnO_2	2060[b] (1127)	.....	
Zinc	ZnO	3272[a] (1800)		Zinc vaporizes before oxide is formed. Refractory. Easily fluxed.

[a] Sublimes. [b] Decomposes. [c] Loses oxygen at temperature indicated.

The best method thus far discovered for preventing porosity in the weld metal is to blanket the molten weld metal with a low solubility gas, a flux or with an impervious liquid film. Silicon is the only element thus far found to develop a satisfactory film of this type.

Oxygen, Oxides.—Except for the fuel gases, oxygen from the air and/or from

Oxides at Room Temperature and Soft-Soldering Temperature.—Since copper, brass and bronze will tarnish* at room temperature, the film thus formed is superficial and is no obstacle whatever

* Sulfur gases are responsible for this tarnish more than is oxygen. Copper, on long exposure to the atmosphere, reacts with sulfur and carbon gases, water and oxygen to form a *patina* (film) which protects the copper from further attack.

to soft-soldering operations. This is also true of the copper-cadmium alloys, tin alloys, zinc alloys and copper-nickel alloys.

The alloys of copper with aluminum, beryllium and chromium, and, to a certain extent, also with silicon are difficult to soft-solder due to the existence of a thin, unfluxible (with soft-soldering fluxes) film of the respective oxide.

In the case of the copper-silicon alloys, the silicon oxide does not form to an interfering extent at room temperature though it does as soon as the metal is heated to soft-soldering temperatures. The soft soldering fluxes are ineffective on silicon oxide. Hence, in order to soft-solder the copper-silicon alloys, it is necessary, starting with freshly cleaned metal, to first coat the surfaces with flux and then heat to soft-soldering temperature and solder as quickly as possible.

Gassing of Oxygen-bearing Copper.—The *gassing* of oxygen-bearing copper is due to a reaction that takes place in the hot, solid copper in an atmosphere containing hydrogen. The particles of cuprous oxide in the metal are reduced by hydrogen that has diffused into it, thus

$$Cu_2O + H_2 = Cu_2 + H_2O$$

This reaction begins with a temperature of about 750°F. (400°C.) in the copper and increases with the temperature. It is not obtained with an oxygen-free or a deoxidized copper or other copper alloy. It may cause a loss of as much as 50% in strength in a weld in oxygen-bearing copper.

The action of arc- and gas-welding heat on copper containing cuprous oxide will cause some rejection of the latter to the grain boundaries with some weakening effect. Thus, in carbon-arc welding of tough-pitch copper an efficiency of only 70 to 90% may be expected in the weld even if there is no hydrogen present in the arc atmosphere. The use of a deoxidized copper base metal avoids weaknesses resulting from the presence of cuprous oxide in the base metal.

Copper, when heated to redness in air or oxygen, always develops two oxides, the black cupric oxide, CuO, at the oxide-air interface and the ruby red cuprous oxide, Cu_2O, at the copper-copper oxide interface. Neither of these oxides on the surface of the solid metal or molten weld metal offers any difficulty in welding, brazing or soft-soldering operations. They are easily fluxed and reduced.

Deoxidized Copper.—Copper sheet and plate which is to be joined by fusion welding should be manufactured especially for the purpose. This type of copper is commonly deoxidized with phosphorus of which only about 0.01 to 0.05% remains in the metal. The deoxidized copper may also be deoxidized with silicon.

Most of the major alloying elements used with copper are more active chemically than copper and, therefore, form oxides preferential to copper or reduce copper oxide if present in the molten metal. Hence, in brazing or welding operations in copper alloys, the major concern is surface oxides.

Effects of Major Alloying Elements

Aluminum.—Aluminum bronzes having aluminum up to 10% in wrought metal, and up to 14.5% in cast metal, the remainder being copper alone or copper with minor additions of iron, nickel, tin, and/or manganese, are characterized in the hot, solid state by good ductility and nonscaling qualities. The scale-resisting property is due to a thin, continuous coating of the refractory aluminum trioxide, which is also responsible for the difficulty encountered in gas welding the aluminum bronzes.

Ordinary blanketing action of the metal with the oxy-acetylene gases and usual fluxes is futile as the aluminum will reduce water vapor or take oxygen from the borax flux. In carbon-arc welding, the metal is melted rapidly and a very satisfactory weld can be made. Shielded metal-arc welding is done in more than one pass and the oxide should be ground from the surface before a second deposit is made. The aluminum bronzes have excellent strength, hardness and wear-resistant properties which are obtainable to a considerable extent in a properly applied weld metal.

Arsenic.—Arsenic causes no interfering or beneficial metallurgical reactions in welding operations. It is used in locomotive firebox and staybolt copper in Europe to improve the workability, strength and fire resistance of copper at elevated temperatures.

Beryllium.—Alloyed with copper to the extent of $2^1/_2$% or less, beryllium forms

a high-strength, heat-treatable alloy which is difficult to gas weld because of the formation of the refractory, continuous, unfluxible oxide on the molten metal. It becomes folded into new deposits preventing a satisfactory confluence of the newly fused metal with that previously melted. The more rapid action of the carbon arc makes it possible to form a satisfactory fusion weld or to flow beryllium copper on solid copper or steel. Such welds are soft, and a full heat treatment is necessary to obtain full strength. In deposits of two or more passes, the oxide of the first pass should be ground off before another deposit is made.

Cadmium.—This element in copper to the extent of 1¼% offers no serious difficulty in arc- and gas-welding operations. It evaporates rather easily at the welding temperature of its copper alloy. A small amount of the heavy oxide may be entrapped in the molten metal, but as it is fluxed without difficulty, this is not serious. It is welded by gas and carbon-arc welding.

Chromium.—Like aluminum and beryllium, chromium forms on the weld pool of the copper-chromium alloy (which rarely contains more than 1% chromium) a refractory oxide which makes gas welding difficult except with special fluxes. Carbon-arc welding is possible, but the weld requires a full heat treatment to enable the maximum hardness, strength and conductivity to be obtained.

Iron.—Used in very limited proportions of 0.5 to 1% in manganese bronze and somewhat higher proportions in aluminum bronze, iron interposes no difficulty in gas or arc welding.

Lead.—Pure lead can be gas welded without difficulty though the weight and fluidity of the molten metal make vertical or overhead welding difficult. In the copper alloys, it gives trouble in neutral flame, gas welding by reason of hot-shortness and high specific gravity and instability of the oxide.

Lead is used in cast copper alloys in amounts of 0.5 to 20% and from 0.5 to 3.5% in the forged, extruded and drawn copper alloys to make them freely machinable. It does not alloy with copper, brass or bronze to any appreciable extent but exists in the solid metal as very small droplets of nearly pure lead. Lead in a bronze bearing acts to a limited extent as a solid lubricant. It melts and begins to sweat onto the surface as soon as the temperature of the solid copper, brass or bronze reaches 621°F. (327°C.)

Manganese.—This element, occurring in the usual commercial copper alloys such as manganese bronze, manganese deoxidized copper and copper silicon alloys in proportions of 0.05 to 1¼% offers no difficulty in gas-or arc-welding operations The high oxide is unstable, but the low one is not, and it is readily fluxed. In copper alloys containing no silicon, manganese is evidenced in gas welding by the presence of high-velocity, dull red sparks from the melting metal. In any alloy containing both manganese and silicon, no sparks are thrown off, but the manganese oxide combines with the silicon and copper oxides to form a low-melting, flux-like glass.

Manganese is used as a deoxidizer and desulfurizer in the copper-nickel alloys. High-manganese copper alloys have special electrical resistance properties but have little interest in welding.

Nickel.—The nickel oxide does not form on the hot, solid metal at as low a temperature as do the oxides of aluminum, beryllium, chromium and silicon. The copper-nickel alloys are, therefore, easier to soft-solder than alloys containing these other four elements. In brazing operations, the nickel oxide offers no appreciable interference.

In gas welding, however, the nickel oxide may interfere with the flowing of the metal. It is a closely clinging, refractory film which causes the metal to solidify with a rough, cinder-like surface. Difficulties from this source can be avoided by the initial application of a heavy paste of boron suboxide or other suitable flux.

In all of the copper-nickel alloys, it is important that there be sufficient deoxidizer or desulfurizer so that there will be a residual amount of a few hundredths of one percent in the solidified weld metal. Manganese is the element most often used for this purpose. In the nickel silvers, the zinc serves in this manner as well as being a major alloying constituent.

Difficulty from the nickel oxide is also avoided by the use of coated electrodes.

Nickel, added to copper in proportions from 10 to 30%, improves strength and durability and confers a white color to the alloy.

Phosphorus.—When used in larger

amounts than 0.25%, as for example 4 to 8%, phosphorus acts much the same as when used in smaller amounts, i.e., the phosphorus will evaporate slowly from the melt keeping the oxide from forming on the surface and resulting in a bright weld pool.

In small amounts, leaving 0.01 to 0.50% in the metal, as in phosphor bronze, phosphorus acts as a powerful deoxidizer for copper and tin, the resulting phosphorus oxide evaporating from the melt.

Except in phosphorous-copper brazing alloys, phosphorus is not used as an alloying element in the copper alloys. Its benefits, including improved soundness, are the indirect result of its deoxidizing effect and improved fluidity of the molten metal.

Silicon.—Silicon is used both as a deoxidizer and as a major alloying element to improve strength, workability and ductility. The alloy containing it cannot be melted either by gas or arc welding without the formation of a continuous film of liquid glass on the weld pool. The silicon oxide forms on the solid metal at temperatures as low as 400°F. (204°C.) interfering with soft-soldering operations unless a flux is applied before the metal is heated. On the molten metal, this film is flux-like in nature and protects it from further oxidation and contamination from the welding gases. It offers no difficulty in brazing operations with silver alloys.

Water vapor in the weld metal may cause porosity. If it is permitted to come up through the weld metal when the latter is being quickly fused and quickly solidified, a bad bright-surfaced porosity develops in the weld metal. This is attributed to the reaction $2H_2O + Si = SiO_2 + 4H$. In oxy-acetylene welding, the much longer heating period allows the water to evaporate from the plates and flux before actual fusion begins, and the water vapor in the torch flame cannot get into the metal through the impervious liquid silica glass film. Gas welds are, therefore, quite free from this type of porosity. Inert-gas metal-arc welds may be especially strong and sound.

The copper-silicon alloys have good ductility at room temperature and also at elevated temperatures, having exceptionally good forgeability in the range between 1200°F. (649°C.) and 1600°F. (871°C.). Near the melting point, the metal is hot-short and care must be exercised in bending or stressing the metal until its temperature has dropped below 1700°F. (927°C.). In the case of arc welding, the time in passing through this hot-short temperature range is very brief so that little trouble is experienced from contraction during this critical range except in laying on the initial bead in very heavy and rigid plates.

Silver.—Owing to its cost, silver is not commonly used as a major alloying constituent except as a silver brazing alloy. As a minor constituent, in proportions up to 0.04%, it is responsible for a decided improvement in the annealing temperature of copper. In amounts of approximately 1%, it is used in copper welding rods with a very slight advantage in causing a lowered melting point and smaller grain size. It does not improve the strength, soundness or ductility.

Tin.—Tin is one of the four most important major alloying elements used with copper. It is employed in amounts up to 11% in wrought alloys and in larger amounts up to 30% in cast alloys. Tin has a decided hardening and strengthening effect on copper. The phosphor bronzes have excellent durability and wear resistance.

In welding operations where the tin is not protected by a deoxidizer, such as phosphorus or zinc, the tin oxidizes preferentially to the copper, and the tin oxide is prone to be caught in the weld metal making the latter weak. The tin oxide is, however, easily fluxed. It does not form a complete crust over the weld pool as do some of the elements mentioned above. Tin has a high boiling point so that no metal is lost by evaporation even when superheated with the torch or arc.

Zinc.—Zinc is commercially the most important alloying element used with copper. It is used in cold- and hot-worked brasses in amounts up to 41% and in brazing alloys in amounts up to 50%. A characteristic of all of these copper-zinc alloys is the relative ease with which zinc is evaporated from the molten metal with but very slight superheat.

The zinc oxide is easily fluxed. Very little of it appears on the molten weld unless a strongly oxidizing flame is used, in which case a film forms which suppresses, in a large measure, the further evaporation until the metal is given an appreciable superheat. A film of silica

glass is also useful in this respect, a fractional percent of silicon being a constituent of many of the yellow bronze welding rods.

These welding rods all have sufficient zinc, 38 to 41%, to develop in the weld metal a considerable proportion of the hard, strong beta brass constituent. Fortunately, this beta constituent is soft and ductile in the temperature range between its melting point and about 875°F. (468°C.). Hence, there is no danger of hot-short cracks forming in such weld metal, and residual stresses do not build up to serious proportions even when such weld metal is used in very rigid welds in heavy cast-iron and steel sections.

Zinc does not cause so abrupt a reduction in electrical and thermal conductivity in copper as do many of the other elements. The brasses, therefore, require considerable heat when being welded, especially with zinc contents of 5 to 15% —the gilding metals, commercial bronzes and red brasses.

Effect of High-Thermal Conductivity of Copper

The high-thermal conductivity of copper, commercial bronze and red brass should be mentioned as it is the property which gives the most trouble in welding operations. Thus, in raising the temperature of the edge of a copper sheet to the fusion point, difficulty is experienced owing to the rapid transfer of the heat to the more remote parts of the metal.

It is often necessary, therefore, to preheat before the welding temperature can be attained in the desired location. The preheat temperature may be from 600 to 1000°F. (316 to 538°C.) in the area near the weld before actual welding can be done with any reasonable speed.

In spot and seam welding, the electrical and thermal conductivities of copper make these processes difficult if not commercially impracticable.

However, brass, bronze, the copper-nickel and copper-silicon alloys can be readily spot and seam welded though special procedures are sometimes required. A small addition of silicon to brass improves the latter materially for such joining methods.

Effect of Welding Heat

The cold-work strength obtainable in a copper alloy may be, in the case of some spring wire, as much as 350% of the annealed strength, but usually for copper and brass it varies from 110 to 200% of the annealed strength depending upon the degree of strength, hardness and residual ductility desired.

An application of heat of sufficient intensity and for a sufficient time to a copper alloy which has been thus cold-work hardened, will first cause relief of its residual stress and then recrystallize and soften the metal. The temperature at which this softening or annealing begins depends upon the composition and upon the amount of previous cold-work. In general, it is lowest for pure copper, a temperature of 374°F. (190°C.) for a short time causing some softening. Hence, cold-rolled, pure copper can be softened appreciably by the moderate temperatures, 420 to 470°F. (216 to 243°C.), used in soft-soldering operations. The higher temperatures of brazing and welding will, of course, anneal it completely.

Copper for fabrication into sheets, tubes and wires, which are strengthened by cold-work, is often improved in its annealing temperature by small additions of other elements. Thus, the additions of elements used singly will raise the softening point of cold-worked copper to approximately the following temperatures:

Element	% Added to Copper	Approximate Softening Temperature of Work-Hardened Copper, °F.
Silver	0.10	617 (325°C.)
Arsenic	0.10	482 (250°C.)
Phosphorus	0.10	617 (325°C.)
Antimony	0.10	707 (375°C.)

Thus, the alloying of the copper with only a few hundredths percent of one of these elements will make it quite resistant to any heat effect (softening) in soft soldering operations. Cold-drawn deoxidized copper tubing, for example, which carries 0.01 to 0.03% phosphorus can be safely soft-soldered with little, if any, annealing effect.

Where the copper is alloyed with appreciable amounts of other elements as is the case with brass, bronze, copper-silver, copper-nickel, aluminum bronze and copper-cadmium alloys, etc., the softening effect of heat rarely begins at temperatures below 500°F. (260°C.) and even at temperatures as high as 1200°F. (649°C.), and an appreciable length of time is required for complete annealing. Hence,

most of these cold-worked commercial copper alloys may, as far as softening effect is concerned, be soft-soldered with no loss of strength. Also, since the heating period for most brazing operations with silver alloys is so short, they may be silver-brazed at 1200°F. and still retain a considerable proportion of their cold-work strength.

Aside from precipitation-hardening treatments in the beryllium, chromium and nickel-silicon copper alloys, the manner of cooling, i.e., slow cooling or quench cooling from a high temperature, makes little difference with most copper alloys. The metal will be soft anyway. This is true of copper alloys in the alpha phase, such as:

Copper and deoxidized coppers with 98% copper or higher.
Brasses with 35% or less of zinc.
Bronzes with 8% or less of tin.
Cupro-nickels with 30% nickel or less.
Copper-silicons with 3% or less of silicon.
Nickel silvers with 25% or less of zinc and 18% or less of nickel.
Aluminum bronzes wth 8% aluminum or less.
Copper-cadmiums with 1% cadmium or less.
Copper-manganeses with 20% manganese or less.

The above alloys can be hardened only by cold-work, not at all by heat treatment, welding, brazing, etc.

There are, however, some important copper alloys which have other than the solid solution (alpha) metallurgical phase which may be affected by quick cooling. For example, such alloys as those with zinc, tin, aluminum, silicon and/or cadmium, having higher percentages than those noted above for the approximate upper limit of the alpha phase, may retain more of the beta phase if quenched from the annealing temperature than if slow cooled.

Beta brass, for example, may be harder if quenched from the annealing or welding temperature than if slowly cooled, though the difference is slight compared to the sharp difference in hardness between quenched and slowly cooled high-carbon steels. This effect explains in a measure the excellent strengths and hardnesses obtainable with cast metal and weld metal in the manganese bronzes, Tobin bronze, extruded brasses, high-tin and high-aluminum bronzes.

In the case of the precipitation-hardening metals, beryllium-copper, chromium-copper and nickel-silicon-copper alloys, heating effects depend on the initial condition of the metal. If the metal is in the solid solution condition, i.e., softest condition, heating for a limited time and temperature will harden the metal, though in every case the welding temperature is too high for this purpose, and the fused metal will be soft though the surrounding metal may be hardened.

If the metal has already been given its precipitation-hardening treatment, any further heating at a higher temperature will cause softening to some degree.

Chromium copper will operate at reasonably high service temperatures, e.g., as resistance spot, seam and flash-welding electrodes, after it is given its full hardening treatment, without undue softening.

An elevated temperature for a suitable time will stress-relieve copper alloys as readily as is the case with the ferrous metals. However, it is rarely necessary to resort to such measures to relieve locked-up stresses resulting from welding operations. It is sometimes necessary in order to prevent *season cracking* to reduce the residual stress resulting from severe cold-work on high-zinc brass. high-silicon alloys, nickel-silver, aluminum and manganese alloys, and phosphor bronze.

Unimportant in copper alloys in the as-cast or as-welded state, but of major importance in cold-worked metals which are to be reheated, is the recrystallizing effect. Cold-worked metal has absorbed and retained some of the cold-work energy imparted to it in the cold-rolling, cold-drawing or cold-hammering, bending, pulling or twisting operations.

The energy is not, however, absorbed uniformly by a volume of metal nor by the volume of a crystal (grain) of the metal. There are high points and low points of this energy distribution. Hence, when the metal is heated as in a welding or annealing process, the points of high energy act as focal points for new grains, and the metal recrystallizes when a suitable temperature is reached. These grains grow as the temperature is increased so that the size of the grains is taken in some cases as a measure of the heating temperature value.

In common with most other metals, copper alloys will develop a bond rapidly with soft solders and brazing alloys. Not much information has been published on the exact mechanism of this bond.

Aside from the effects described above, the only other result of welding or brazing operations on copper and copper alloys in the solid base metal adjacent to the weld is a slight enlargement of the grain. Since this grain size rarely becomes so great as that of the weld metal, it may usually be disregarded. No harmful chemical or solution changes take place in the heat-affected zone except in the case of beryllium-copper, nickel-silicon copper or chrome copper in which there may be an undesirable softening of the heat-treated alloy.

In none of the copper alloys is there a hard, brittle constituent developed comparable to the martensite in chilled steel. No matter how quickly the weld metal is solidified and cooled, it is always relatively soft and the yield strength relatively low. Hence, a stress-relief heat treatment is not so necessary in the copper alloys as it is in the ferrous metals.

However, the weld metal in a copper alloy weld in common with other metals partakes of the nature of soft cast metal with large grains and a columnar structure. It may be desirable, therefore, to give the weld metal a suitable aftertreatment when a fine grain with the maximum in strength and ductility of the finished weld is required.

The aftertreatment which is most effective is a severe peening of the cold weld metal followed by a short-time anneal at 1200°F. (649°C.). A slow passage of the oxy-acetylene flame along the peened weld, bringing the metal to a very dull red estimated at 1100 to 1200°F. (593 to 649°C.), is sufficient to recrystallize the metal without fully softening it.

Hot forging of the weld in copper will improve its quality, but it is not often applied in this country.

Mill processes such as cold-rolling or cold-drawing followed by an anneal will recrystallize and very nearly obliterate a resistance flash weld, an autogeneous arc weld or a silver braze (except for the actual silver-brazed surfaces).

ALUMINUM AND ALUMINUM ALLOYS

An understanding of the metallurgical effects of welding products of aluminum and aluminum alloys requires some basic knowledge of the properties and structures. There are two broad classifications of aluminum alloys, i.e. (1) non-heat-treatable and (2) heat-treatable. Strengths of pure aluminum and the non-heat-treatable alloys are developed by strain-hardening and by alloying elements which effect some increases in strengths either as dispersed phases or solid solutes in the aluminum. Manganese is the principal dispersoid type alloying element and alloy 3S the chief example. Magnesium is the principal soluble alloying element in the non-heat-treatable class of aluminum alloys, with 4S and 52S the chief examples. In the annealed or soft temper (—O), the composition of the alloy wholly controls the strengths while in the strain-hardened or —H series of tempers the degree of strain-hardening is the controlling factor.

The alloying elements in Class 2 aluminum alloys are dissolved in the aluminum at a high temperature by a process commonly known as solution heat treatment, and maintained in solid solution by quenching from this temperature. The solution of specific elements or compounds in aluminum governs the strengths of these alloys in the *as-quenched* temper. Additional increases in strengths are effected by precipitation of a portion of the soluble elements in finely divided form. Precipitation may take place at room temperature following quenching or may be accelerated by a thermal treatment at a moderately elevated temperature (i.e., 210 to 350°F.) (99 to 177°C), producing the —T4 or —T6 tempers. Alloys susceptible to either of these precipitation treatments are designated as *age-hardenable*. Strengths may also be increased by strain-hardening after heat treatment which may or may not be followed by artificial aging. In the annealed or soft temper (—O), the composition of the alloy wholly controls the strengths as is the case with the non-heat-treatable alloys.

The heat-treatable alloys can be divided into classes containing the following principal alloying elements:

Elements	Alloys
(*a*) Mg and Si	53S, 61S, 63S, R353 and R361
(*b*) Cu and Mg, Cu, Mg and Si (duralumin type)	24S, 14S, and Hard-clad R301
(*c*) Zn, Mg and Cu	75S

The heat of welding decreases the strengths of both non-heat-treatable and

heat-treatable aluminum alloys and may in some cases also lower their resistance to corrosion. The effects of strain-hardening in the non-heat-treatable Class 1 are partially or wholly destroyed by heat, depending upon the temperature attained coupled with the time maintained at temperatures of about 400°F. (204°C.), or more. The effects of solution heat treatment and precipitation treatments for Class 2 aluminum alloys are adversely affected by the heat of welding. The extent of the detrimental effect increases with temperature and time at temperatures over 400°F. (204°C.). The alloys containing substantial amounts of copper suffer not only from loss of strength but also from loss in resistance to corrosion when subjected to the heat of welding.

The factors determining the heat of welding are multiple; however, two of the controlling conditions in welding and brazing are the melting point of the base or plate material, and the melting point of the filler metal. It is possible to weld thin sections of aluminum without employing filler metal. The exact thermal cycle through which the materials progress or the rate of heating and cooling is determined mainly by the welding process, the thickness of the part, and the geometry of the joint.

In welded or brazed joints there are always two types of material to be considered: i.e., the weld metal or deposit, which is a casting; and the plate or base material which may be wrought or cast.

The physical properties of cast aluminum in the weld zone are influenced by the composition and the rate of solidification. Cast metal is not as strong or as ductile as wrought metal, in general, for a given aluminum alloy.

The weld deposit, when filler metal is used, is an alloy formed from a mixture of the filler metal with the base metal. The extent of fusion and incorporation of either base metal or sublayer of added weld metal, in multipass welds, is a function of the filler metal, plus the welding technique and all the factors affecting heat input and transfer away from the molten pool. A high rate of cooling is usually desirable for attainment of maximum strength.

Alloys do not solidify at a fixed temperature but over a range. Solidification begins at the liquidus and is complete at the solidus with a resultant mixture of solid and liquid extending over what is called the *mushy stage.* (See Fig. 2.) It is preferable for a filler metal to have a low melting point and to solidify over a range. Thus, when the weld metal cools the filler metal solidifies last and the contraction stresses that are sometimes sufficient to cause cracking at the edge of the weld bead are taken up by the casting in the mushy stage during solidification. The filler metal must have a high degree of fluidity, and have sufficient strength and ductility at elevated temperatures to withstand the stresses imposed by the thermal and solidification contractions. Since the fusion zone is apt to be weak in welds of aluminum alloys, the importance of the composition and structure of this alloy must be recognized.

The selection of filler metal is based on welding characteristics, such as fluidity and cracking tendency, on corrosion requirements or strength requirements. The alloy 2S (commercially pure aluminum) is employed as filler metal when maximum resistance to corrosion and high ductility are of prime importance in the weldment and strength is a minor factor. The alloy 43S, which contains 95% aluminum and 5% silicon, is generally employed where greater strength is required. Other aluminum alloys, including parent or base metal, are employed on occasion for specific applications when the strength or resistance to corrosion requirements of the weldment are such that special procedures or welding technique may be employed.

The effect of the welding process upon the aluminum-base metal varies with distance from the weld and may be divided roughly into areas which reflect the temperatures attained by the metal. Obviously, these areas or zones are not sharply defined as the heat distribution changes from point to point.

The width (See Fig. 1, Chapter 32) of these areas or their distance from the weld will vary with the welding process and the thickness or geometry of the part. The strengths of the base metal may be fairly high in the solid solution area which is always quite narrow. The annealed area is broader, usually extending about four to six times the thickness of the material on each side of the joint, and the strengths are considerably lower resulting from the precipitation of soluble constituents as coarse particles. The

overaged zone is characterized by excess precipitation of finely divided particles. Strengths are somewhat lower than those of the unaffected zone at a greater distance from the weld. The areas for the non-heat-treatable alloys are usually limited to three as shown in Fig. 2 of Chapter 34.

Reheat treatment after the welding operation is sometimes feasible and results in a substantial increase in joint strength. The design and geometry of the part determine the practicability of such an operation. Heat treating after welding dissolves soluble constituents in the weld metal and all of the coarse and fine precipitated particles in the base plate. A more homogeneous condition results throughout the cast and wrought materials, respectively. Quenching retains this solid-solution condition while subsequent precipitation, at room temperature or at a moderately elevated temperature when artificial aging is employed, takes place fairly uniformly in the form of finely divided particles. Thus, the maximum strengths and resistance to corrosion of the base plate are realized, however, with a sacrifice in ductility, and the strength of the joint is dependent upon that of the cast material in the weld zone.

The metallurgical effect when welding the cast alloys is similar to that described above for the wrought materials. Foundry welding to salvage cast parts by rewelding defects is frequently required. In this case, welding should be completed prior to heat treatment. The welding of cast to wrought parts, e.g., in the form of cast fittings or tubing or tankage, is also done. Some impairment of heat treatment in the casting is obtained after welding and this must be considered in arriving at the cross sections to carry the loads. It is not usually feasible to heat-treat, after welding castings to wrought parts.

BIBLIOGRAPHY

1. *A List of Alloys*, Wm. Campbell, American Society for Testing Materials.
2. *The Heat Effect in Welding*, W. G. Theisinger, The Iron Age, Oct. 15, 1936, December 17, 1936, February 25, 1937, and March 4, 1937.
3. *Investigation of Arc and Gas Welded Joints in Aluminum and Aluminum Alloys*, R. K. Wells and A. G. Bissell, The Welding Journal Res. Suppl., November 1938
4. *Alloying Elements in Steel*, E. C. Bain, American Society for Metals, 1939.
5. *Isothermal Transformation in Steels*, E. S. Davenport, Transactions of American Society for Metals, 1939.
6. *The Structure of Metals and Alloys*, Wm. Hume-Rothery, Chemical Publishing Co., 1939.
7. *The Value of Electric Arc Welding in Design and Its Limitations*, I. Harter, J. C Hodge and C. J. Schoessow, The Welding Journal, September 1939.
8. *The Thermal Distribution and Temperature Gradient in the Arc Welding of Oil Well Casing*, W. A. Bruce, Journal of Applied Physics, October 1939.
9. *Practical Metallurgy*, George Sachs and K. P. Van Horn, American Society for Metals, 1940
10. *The Role of Temperature Control and Measurement in the Welding of Oil Well Casing*, L. R. Hodell, The Welding Journal Res. Suppl., February 1940.
11. *Metallurgical Changes at Welded Joints and the Weldability of Steels*, R. H. Aborn, The Welding Journal Res. Suppl., June 1940
12. *Welding Magnesium and Its Alloys*, W. Spraragen and G. E. Claussen, The Welding Journal Res. Suppl., August 1940.
13. *Principles of Physical Metallurgy*, G. E. Doan and E. M. Mahla, McGraw-Hill Book Co., 1941.
14. *The Tee-Bend Test to Compare the Welding Quality of Steel*, G. A. Ellinger, A. G. Bissell and M. L. Williams, The Welding Journal Res. Suppl., March 1942.
15. *A Tentative System for Preserving Ductility in Weldments*, G. E. Doan, R. D. Stout, J. H. Frye, Jr., and S. S. Tor, The Welding Journal Res. Suppl., July and September 1943.
16. *The Measurement of Cooling Rates Associated with Arc Welding and Their Application to the Selection of Optimum Welding Conditions*, W. F. Hess, L. L. Merrill, E. F. Nippes, Jr., and A. P. Bunk, The Welding Journal Res. Suppl., September 1943.
17. *Weld Bead Hardness Tests on Some Carbon, Nickel and Nickel-Chromium War Department Steels*, O. E. Harder and C. B. Voldrich, The Welding Journal Res Suppl., September 1943.
18. *Conditions of Fracture in Steel*, J. H. Hollomon and C. Zener, Trans American Institute of Mining and Metallurgical Engineers, 1944.
19. *The Welding of Copper Alloys*, C. E. Swift, The Welding Journal, April 1944.
20. *Determinations of Cooling Rates of Butt and Fillet Welds as a Result of Arc Welding with Various Types of Electrode on Plain Carbon Steel*, W. F. Hess, E. F. Nippes, Jr., L. L. Merrill and A. P. Bunk, The Welding Journal Res. Suppl., August 1944.
21. *The Effect of Postheat in Welding Medium-Alloy Steels*, M. A. Pugacz, G. J. Siegel, J. O. Mack, The Welding Journal Res. Suppl., October 1944.
22. *The Measurement of Energy Absorption in Tee Bend Test*, L. C. Bibber and J. Heuschkel, The Welding Journal Res. Suppl., December 1944.
23. *Handbook of Chemistry and Physics, 1915*, Chemical Rubber Publishing Co.
24. *Weldability of Manganese Silicon High Tensile Steels*, G. G. Luther, F. H. Laxar and C. E. Jackson, The Welding Journal Res. Suppl. April 1945.
25. *Application and Development of Modern Heavy Coated Arc Welding Electrodes*, D. C. Smith and W. G. Rinehart, The Welding Journal, June 1945.
26. *Some Causes of Brittle Failures in Welded Steel Structures, H. E. Kennedy*, The Welding Journal Res. Suppl., November 1945.
27. *The Quantitative Measurement of Weld-*

ing Response by Bead Welds, R. D. Stout, S. S. Tor and G. E. Doan, The Welding Journal Res. Suppl., December 1945.

28. *DeForest Brittle Temperature Research,* P. R. Shepler, The Welding Journal Res. Suppl., June 1946.

29. *Final Report of a Board of Investigation Convened by Order of the Secretary of the Navy to Inquire into the Design and Methods of Construction of Welded Steel Merchant Vessels,* July 15, 1946.

30. *An Investigation of the Effect of Welding on the Transition Temperature of Navy High-Tensile Low-Alloy Steels,* G. G. Luther, C. E. Hartbower, R. E. Matius and F. H. Laxar, The Welding Journal Res. Suppl., October 1946.

31. *A Review and Summary of Weldability Testing Carbon and Low-Alloy Steels,* G. G. Luther, C. E. Jackson and C. E. Hartbower, The Welding Journal Res. Suppl., October 1946.

32. *Arc Atmospheres and Underbead Cracking,* M. W. Mallett and P. J. Rieppel, The Welding Journal Res. Suppl., November 1946.

33. *Influence of Geometrical Restraint and Temperature on the Toughness and Mode of Rupture of Structural Steels,* A. R. Anderson and A. G. Waggoner, The Welding Journal Res. Suppl., November 1946.

34. *Some Observations on the Weldability of High Strength Wrought Aluminum Alloys,* W. R. Apblett, The Welding Journal, November 1946.

35. *A.S.T.M. Standards,* Part I-B, Copper and Copper Alloys, American Society for Testing Materials, 1946.

36. *The Effect of Welding Technique on Brittle Transition Temperature,* H. Grossman and P. R. Shepler, The Welding Journal Res. Suppl., June 1947.

37. *Report on the Fracture of Metals,* M. Gensamer, E. Saibel and J. T. Ransom, The Welding Journal Res. Suppl., August 1947.

38. *The Strength of Welded Joints at Low Temperatures and the Selection and Treatment of Steels Suitable for Welded Structures,* Otto Graf, The Welding Journal Res. Suppl., September 1947.

39. *Metallurgical Factors in the Embrittlement of Welded Plate,* R. D. Stout and L. J. McGeady, The Welding Journal Res. Suppl., November 1947.

40. *Metals Handbook,* American Society for Metals, 1948.

41. *Modern Metallurgy for Engineers,* F. T. Sisco, Pitman Publishing Co., 1948.

42. *A method of Evaluating Transition from Shear to Cleavage Failure in Ship Plate and Its Correlation with Large-Scale Plate Tests.* N. A. Kahn and E. A. Imbembo, The Welding Journal Res. Suppl., April 1948.

43. *The Ductility of Steels for Welded Structures,* A. B. Kinzel, The Welding Journal Res. Suppl., May 1948.

CHAPTER 4

GAS WELDING EQUIPMENT AND MATERIALS*

INTRODUCTION

GAS WELDING IS A group of welding processes wherein coalescence is produced by heating with a gas flame or flames, with or without the application of pressure, and with or without the use of filler metal. This fundamental and basic definition implies that the gases are available, that the gas pressures have been regulated to safe working pressures, and that the gases have been conveyed through hoses to a torch and tip. These gases are mixed in their proper proportions in the torch and the mixture is burned at the end of the tip, producing a controllable flame which is capable of developing the intense heat necessary for welding. A clearer understanding of the relationship of these basic units may be obtained from Fig. 1, which illustrates two gas cylinders (one fuel gas, the other oxygen), regulators for reducing cylinder pressure to working pressure, hoses for conveying the gases to the torch and the torch and tip combination where the gases are controlled and mixed.

Each of the units mentioned above plays an essential part in the controlling and directing of the heat employed in gas welding, torch brazing, gas heating, etc. The heat is obtained from combustion of the gases, but the effectiveness of this heat is governed to a large extent by the ability of the operator. Proper training of the operator and careful selection of the equipment used is essential to the production of high quality work.

An analysis of essential welding equipment and its effect on the welded joint is described in detail under the headings that follow.

GASES

Gas welding covers many processes employing different fuel gases. All of these gases, however, react chemically with oxygen in a manner differing little from that of the classic fuels, such as wood, coal or fuel oils, that have been employed for centuries. They all require oxygen to support combustion (burn). Within certain limits the flame temperature increases as the amount of oxygen in the gas mixture is increased.

The three characteristics of all fuel gases that are of major importance as far as welding is concerned are:

1. The maximum flame temperature that may be obtained,
2. The quantity of heat that may be obtained from a unit quantity of the gas, and
3. The chemical action of the flame on the material being welded.

The temperature of the flame is evaluated by either the Fahrenheit or Centigrade scale, while the heat quantity is based upon either the English system measured in British Thermal Units (Btu.) or the metric system expressed in kilogram calories (Kg.-cal.). These units may be converted from one to the other by use of the following factors: 1 Kg.-cal. = 3.968 Btu.

Tables 1, 2 and 3 list some of the intrinsic characteristics of a few of the gases that are commercially available.

Acetylene

The fuel gas most widely used in gas welding is acetylene. A compound of carbon and hydrogen (C_2H_2), the gas contains 92.3% carbon and 7.7% hydrogen by

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* Prepared by a committee consisting of A. F. Chouinard, National Cylinder Gas Co., *Chairman*; E. L. Mathy, Victor Equipment Co.; C. A. McClean, Air Reduction Sales Co.; G. W. Plinke, Henry Vogt Machine Co.; J. H. Zimmerman, The Linde Air Products Co.

weight. It is colorless but has a characteristic sweet and easily distinguished odor, not unlike that of garlic. Acetylene is a highly combustible compound and also liberates heat upon decomposition. Thus whenever it is subjected to excessive heat or pressure, the bonds uniting the carbon and hydrogen atoms break down with a resulting liberation of heat. Acetylene contains a higher percentage of carbon than any of the numerous hydrocarbons. This combination gives the oxy-acetylene mixture the hottest flame of any commercially used gas, the temperature of which has been calculated to be near 6000° F.

tity of water in an acetylene generator at all times.

Acetylene in contact with copper, mercury or silver, especially if impurities are present, may form acetylides. These latter compounds are violently explosive and can be detonated by a slight shock or by the application of heat. For this reason, no alloy containing copper in excess of 67% should be used in any acetylene system.

Generation

Acetylene is the product of a chemical reaction. Calcium carbide (CaC_2) is allowed to react with water. In the action

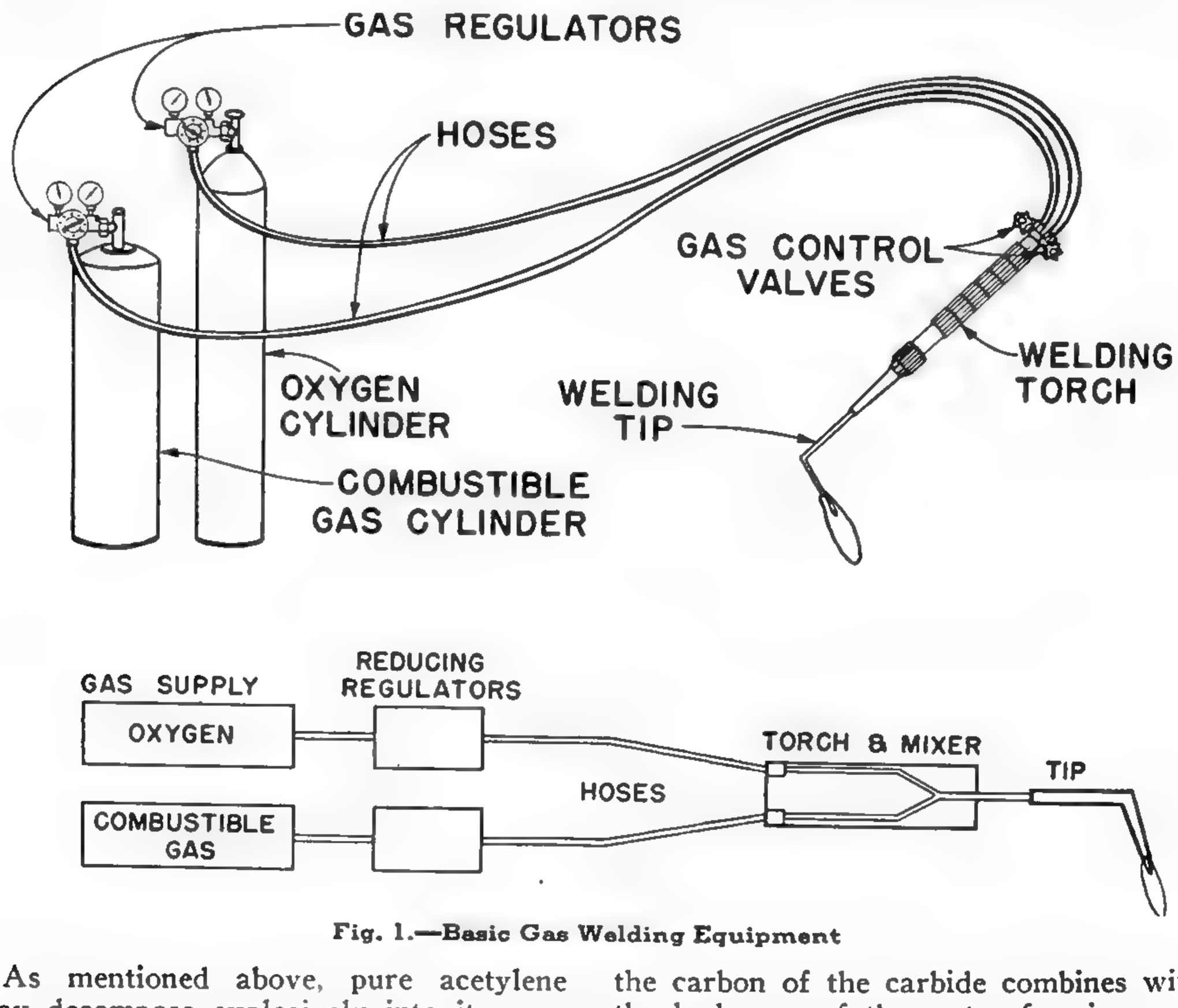


Fig. 1.—Basic Gas Welding Equipment

As mentioned above, pure acetylene may decompose explosively into its constituents with an evolution of considerable heat. At temperatures above 1435° F. or pressures above 30 psi. gage, the gas is unstable and additional heat may start an explosive decomposition that will involve the whole body of the gas. It has therefore become an accepted safe practice never to use acetylene at a pressure exceeding 15 psi. gage. Also, as a protection against excessive temperatures, it is necessary to maintain a prescribed quan-

the carbon of the carbide combines with the hydrogen of the water forming gaseous acetylene, while a whitish residue of calcium hydroxide remains in the water. The chemical reaction equation is:

$$\underset{\text{Calcium carbide}}{CaC_2} + \underset{\text{Water}}{2H_2O} = \underset{\text{Acetylene}}{C_2H_2} + \underset{\text{Calcium hydroxide}}{Ca(OH)_2}$$

The carbide used in this process is produced by the smelting of lime and coke in an electric furnace. Upon being removed from the furnace, it is crushed and

screened for size and packed in airtight containers. The most common size of these containers holds 100 lb. of the hard, grayish solid.

Acetylene Generators.—Three distinct methods are currently employed in the generation of acetylene, namely, the carbide-to-water, the water-to-carbide and the water recession methods. The so-called *carbide-to-water method* is used almost exclusively in the United States. The construction of the generator used for this method allows small lumps of carbide to be discharged from a hopper into a relatively large body of water. This type of generator is schematically shown in Fig. 2. The details of its construction vary with different manufacturers. However, all carbide-to-water generators may generally be classified into two types, low-pressure and medium-pressure generators. The former operates at pressures of 1 psi. gage or less while the latter produces acetylene at from 1 to 15 psi. gage.

water is brought into contact with the carbide by its own change in level. The water is held back by the pressure of the newly generated acetylene above it and as the gas pressure lessens, the water level rises. Then more water and carbide come in contact, and, hence, more acetylene is developed. This in turn, raises the acetylene pressure forcing the water level down.

The generation of acetylene evolves considerable amounts of heat and due to the unstable condition of acetylene at elevated temperatures, this heat must be dissipated. The relatively large volume of water employed in the carbide-to-water generator makes this type the best suited for dissipation of this heat. The water-to-carbide type, on the other hand, uses very limited amounts of water and therefore possesses only slight heat absorbent qualities.

Acetylene generators are available in both stationary and portable units in a great range of types and sizes. Generat-

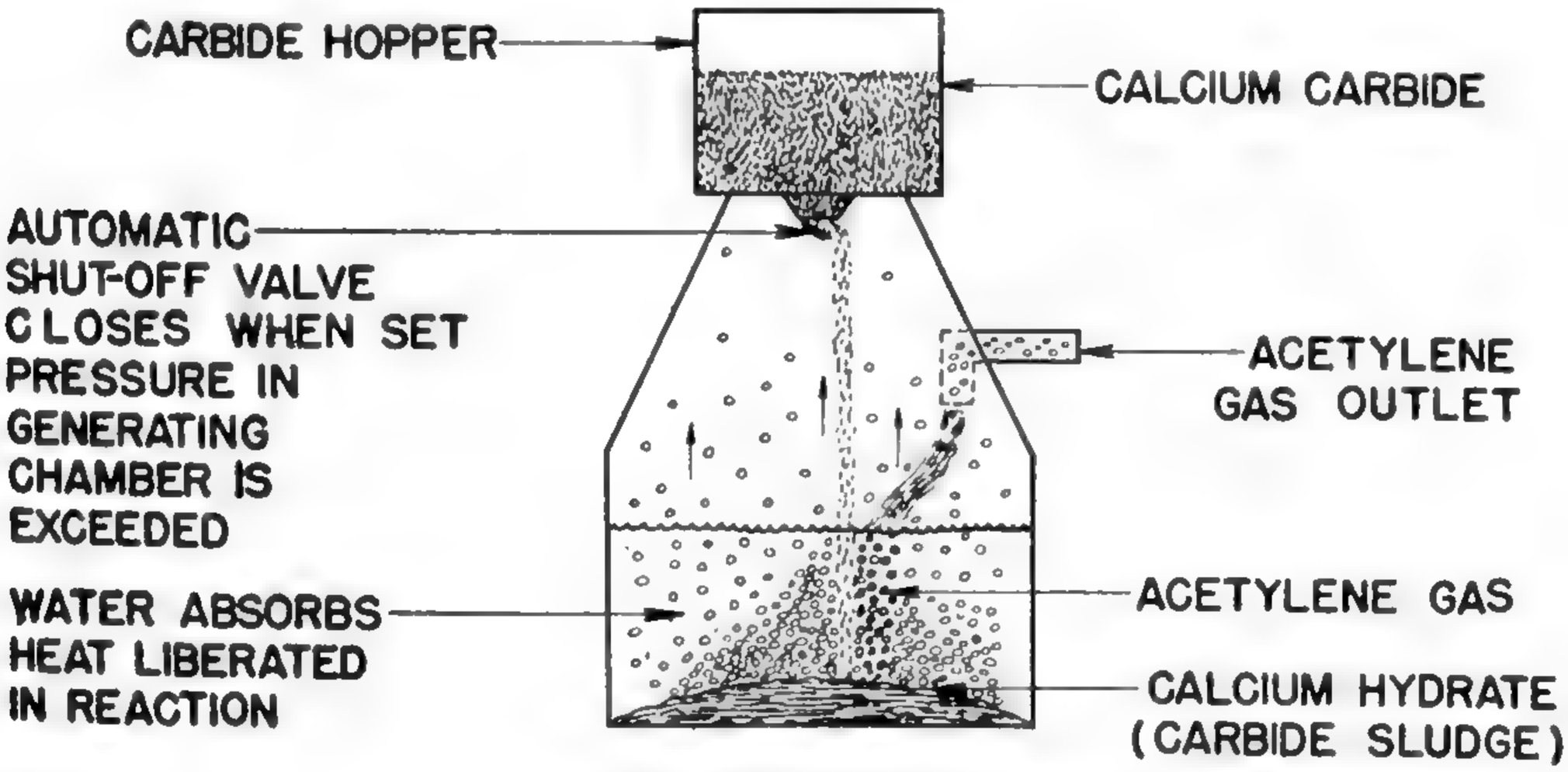


Fig. 2.—Carbide-to-Water Acetylene Generator

A second type of acetylene generator, the *water-to-carbide type,* is used rarely in this country but has a greater popularity in Europe. Its fundamental operating principle is the same as that of the carbide-to-water type but it differs in that water is allowed to drip on the calcium carbide. The carbide used in this method is usually in the form of brick or cakes, so as not to present too much surface area to the water.

Another type of generator is the so-called *water recession type,* wherein

ing capacities of these units range from 12 cu. ft. per hr. for small portable units to 6000 cu. ft. per hr. for the larger stationary industrial installations. Most generators currently in use operate automatically, after an initial setting of operating pressure. They may generate the gas at the rate at which it is used or they may be set to generate at a rapid rate for a short duration of time, in which case the gas is stored and used when required.

The water-carbide ratio employed in the generation of acetylene differs with the

type of installation. Generally, however, one gallon of water is used per pound of carbide. Water-recession generators using specially processed carbide cakes will employ about $^{3}/_{4}$ gallon of water per pound of carbide.

The volumetric rate of acetylene generation per pound of carbide also varies widely with different sizes and types of installation. Single rated automatic generators should be limited to developing about one cu. ft. of acetylene per hr. per pound of carbide. The use of smaller sized carbide in a double rated generator permits generation at a rate of approximately 2 cu. ft. per hr. per pound of carbide. Generators with a high water capacity may increase this production considerably.

Acetylene Cylinders

Free acetylene may, under certain pressure and temperature conditions, dissociate explosively into its constituents. Because of this danger, cylinders to be filled with acetylene are initially packed with a porous filler. To the filler is added acetone, a solvent agent capable of absorbing 25 times its own volume of acetylene per atmosphere of pressure. By so dissolving the acetylene and dividing the interior of the cylinder into small, partly separated cells, a safe acetylene-filled container has been created.

Acetylene cylinders are available in sizes containing from 40 to 300 cu. ft. of the gas. They are equipped with fusible safety plugs as a protection against excessive cylinder pressures. These plugs are composed of a low melting point metal, fusing at about 210° F. When exposed to excessive heat, the plugs melt, allowing the gas in the cylinder to escape.

Safety Precautions

When dealing with acetylene, it must be remembered that the compound is a fuel gas and, as such, will burn readily. Therefore, it must be kept away from open fire. Acetylene should never be used in torch equipment at pressures exceeding 15 psi. gage. Acetylene cylinder and manifold pressures must always be reduced through pressure reducing regulators; acetylene pipe-line pressures should be controlled through suitable pipeline regulators. Cylinders should always be protected against excessive temperature rises and should be stored in well ventilated, clean and dry locations. They must be stored and used with the valve end up.

Hydraulic Seals.—An important protective device is the hydraulic seal or back-pressure valve, which acts to prevent any backfires from passing into the manifold system, the generator or the pipe lines, as the case may be. Essentially, the seal prevents the passage of any fire through the liquid mixture, and also prevents the reverse flow of oxygen or oxy-acetylene mixture back into the manifold supply. These water seals must be an approved type. Also the proper water level must be maintained at all times, to insure reliable and safe operation.

The Oxy-acetylene Flame

The oxy-acetylene flame is easily controlled by valves on the welding torch (see section on Torches and Tips). By changing slightly the proportions of oxygen and acetylene fed to the flame, its chemical characteristics and consequently its action on molten metal can be varied over a wide range.

The complete combustion of acetylene is represented by the chemical equation:

$$2C_2H_2 + 5O_2 = 4CO_2 + 2H_2O$$

which means that 2 volumes of acetylene (C_2H_2) and 5 volumes of oxygen (O_2) react to produce 4 volumes of carbon dioxide and 2 volumes of water vapor. It is evident that for complete combustion, the volume ratio of oxygen to acetylene is $2^{1}/_{2}$ to 1.

When acetylene burns in air, all of the oxygen required for combustion is, of course, obtained from the air. In producing the oxy-acetylene flame, the acetylene is mixed with an equal volume of oxygen in the torch and the additional $1^{1}/_{2}$ volumes of oxygen necessary to complete the combustion are obtained from the air.

Since the mixture issuing from the torch tip does not contain enough oxygen for complete combustion, the following reaction takes place in the zone of the flame right at the tip:

$$2C_2H_2 + 2O_2 = 4CO + 2H_2$$

That is, 2 volumes of acetylene (C_2H_2) and 2 volumes of oxygen (O_2) react to produce 4 volumes of carbon monoxide (CO) and 2 volumes of hydrogen (H_2). It is this reaction that produces the brilliant inner cone of the flame.

In the outer envelope of the flame, the carbon monoxide and hydrogen burn with oxygen from the surrounding air, forming carbon dioxide and water vapor, respectively, as shown in the following two equations:

$$4CO + 2O_2 = 4CO_2$$
$$2H_2 + O_2 = 2H_2O$$

Although acetylene is the fuel gas most widely used in welding and cutting, some other fuel gases are employed. Among the most commonly used are propane, hydrogen, city gas and natural gas. These gases, with the exception of hydrogen, are not used for welding but are sometimes used for brazing. There are other gases available under various trade names, but these generally are commercial combinations of the various basic gases.

Table 1—Ignition Temperatures and Limits of Inflammability of Various Fuel Gases

Name of Gas	Ignition Temperature at Atmospheric Pressure, °F In Oxygen	In Air	Limits of Inflammability in Percentage by Volume at Atmospheric Pressure and Room Temperature In Air Lower	In Air Upper	In Oxygen Lower	In Oxygen Upper
Acetylene	781–824	763–824	2.5	80.0	2.8	93.0
Methane	1033–1292	1202–1382	5.0	15.0	5.4	59.2
Ethane	968–1166	968–1166	3.2	12.4	3.1	50.5
Propane	914–1058	969–1100	2.4	9.5	..	.
Butane	1130	920–1070	1.9	8.4	.	..
Hydrogen	1076–1094	1076–1094	4.0	74.2	4.7	93.9

Propane

Propane (C_3H_8) is a gas used primarily for preheating in oxygen cutting. The main source of this gas is the crude oil gas mixtures obtained from active oil and natural gas wells. Propane is also produced in certain oil-refining processes and from the recycling of natural gas. It is sold and transported in steel cylinders containing from 20 to 100 lb. of the liquefied gas.

Hydrogen

Because of the relatively low temperature of the oxy-hydrogen flame, the use of hydrogen as a fuel gas is largely restricted to certain brazing operations and to the welding of aluminum, magnesium, lead and similar metals. It is also used with oxygen in preheating for underwater cutting. (See Chapter 24 on Gas Cutting.) Hydrogen generally is obtained from the electrolysis of water. Other methods, including the dissociation of ammonia and the Messerschmitt system (hot steam passed over iron filings), also are frequently employed. Hydrogen is available in seamless, drawn, steel cylinders charged to a pressure of about 2000 psi. at 70° F. Because the oxy-hydrogen flame is almost colorless, it is rather difficult to determine when it is neutral. Experienced welders, however, experience little trouble in obtaining the proper oxygen-hydrogen ratio.

Other Fuel Gases

Manufactured gas is a mixture of carburetted water gas and/or coal gas enriched with gas oils or natural gas. Its use as a preheating gas for cutting is limited by high fuel gas requirements.

Natural gas generally is obtained from natural gas wells. Its chemical composition will vary widely with different localities, the principal constituent being methane. Its volume requirements in cutting, however, are, as a rule, about three times those of acetylene although its oxygen to fuel gas ratio is about twice that of acetylene.

Methane, ethane, butane and other hydrocarbon compounds are used occasionally as fuel gases in oxygen cutting and in work where low flame temperatures are permissible.

Comparative studies of the various fuel gases mentioned above may be made by referring to Tables 1, 2, and 3.

Combustion Ratio

An analysis of Column 8 in Table 2 will indicate the volume of oxygen required for complete combustion with any one of the fuel gases. As these data indicate, each unit volume of the particular fuel gas in question requires the number of unit oxygen volumes listed. These values for oxygen are also known as the *oxygen to fuel gas combustion ratios* or, simply, the *gas ratios*, or the *combustion ratios*. By simply multiplying the fuel

Table 2—Constants of Various Fuel Gases

Name of Gas	Chemical Formula	Specific Gravity, 60°F., Air=1.000	Volume, Cu. Ft. per Lb., 60°F., 30 In. Hg.	Weight, lb. per Cu. ft.	Heat of Combustion Btu./Cu. Ft., Dry, 30 In. Hg., 60°F.		Cu. ft./Cu. ft. of Fuel Gas Required for Combustion[a]		Cu. ft./Cu. ft. of Fuel Gas Products of Combustion with Air[b]			Theoretical Flame Temp. with Air, °F.[f, g]	Heat of Formation Constant Pressure, Btu./Cu. Ft.
					Gross[c]	Net[d]	O_2[e]	Air	CO_2	H_2O	N_2		
Acetylene	C_2H_2	0.9056	14.45	0.0692	1483	1433	2.5	11.94	2.0	1.0	9.45	4770	—227.5
Methane	CH_4	0.5545	23.64	0.0423	1012	912	2.0	9.56	1.0	2.0	7.56	3750	103.1
Ethane	C_2H_6	1.0494	12.48	0.0801	1762	1612	3.5	16.75	2.0	3.0	13.23	3820	136.0
Propane	C_3H_8	1.5223	8.61	0.1162	2509	2309	5.0	23.89	3.0	4.0	18.90	3840	167.2
Butane	C_4H_{10}	2.0100	6.51	0.1535	3261	3010	6.5	31.06	4.0	5.0	24.51	3870	202.2
Hydrogen	H_2	0.0696	188.70	0.0053	325	275	0.5	2.39	..	1.0	1.89	4010	....

[a] The volumes are those required for theoretically complete combustion.
[b] The fuel gas products are calculated upon air with a composition of 79% N_2 and 21% O_2.
[c] The gross heat value is the value obtained by burning the gas in a Junker's calorimeter, which assumes that the products of combustion are added to the initial temperature and includes the heat of condensation of the water formed by the combustion.
[d] The net heat value differs from the gross value by the heat of vaporization of water and is calculated from the gross by subtracting the heat of vaporization of water at 60°F.
[e] A portion of these oxygen volumes may be obtained from the atmosphere to supplement oxygen from cylinders.
[f] The flame temperatures are not corrected for dissociation.
[g] With oxygen these temperatures are 5660 for acetylene and 4820 for hydrogen. Values for the other fuel gases not available.

Table 3—Combustion Constants and Composition of Various Manufactured and Natural Fuel Gases

	Blast Furnace Gas	Blue Water Gas	Carburetted Water Gas[a]	Coal Gas[a]	Coke Oven Gas[a]	Some Natural Gases— Follansbee, W.Va.	McKean Co., Pa.	Sandusky, Ohio	Oil Gas[a]	Producer Gas
% Methane	....	....	14.8	34.0	28.5	....	32.3	83.5	27.0	2.6
% Ethane	....	....	....	....	....	31.8	67.0	12.5	....	....
% Propane	....	....	....	....	....	67.7	....	....	....	....
% Ethylene	....	....	12.8	6.6	2.9	....	....	....	2.7	0.4
% Carbon monoxide	26.2	43.4	33.9	9.0	5.1	....	....	....	10.6	22.0
% Carbon dioxide	13.0	3.5	1.5	1.1	1.4	....	....	0.2	2.8	5.7
% Hydrogen	3.2	51.8	35.2	47.0	57.4	....	....	....	53.5	10.5
% Nitrogen	57.6	1.3	1.8	2.3	4.2	0.5	0.7	3.6	3.4	58.8
% Oxygen	....	....	....	....	0.5	....	....	....	....	....
Btu./cu. ft., gross, 60°F., 30 in. Hg saturated H_2O	93	310	578	634	536	2220	1482	1047	516	136
Btu./cu. ft., net, 60°F., 30 in. Hg saturated H_2O	91.6	285	529	560	476	1970	1350	946	461	128
Theoretical flame temperature, °F.[b]	2660	4167	4090	3910	3430	3835	3770	3740	3970	3050

[a] These gases also contain small amounts of benzene and oxygen.
[b] The flame temperatures are not corrected for dissociation and are based upon air with 21% oxygen and 79% nitrogen.

gas volumetric rate by this gas ratio, the theoretical volumetric rate of oxygen is found.

If the maximum flame temperature for a particular gas combination is desired, Fig. 3, which also shows the temperature at various O_2/fuel-gas ratios may be consulted.

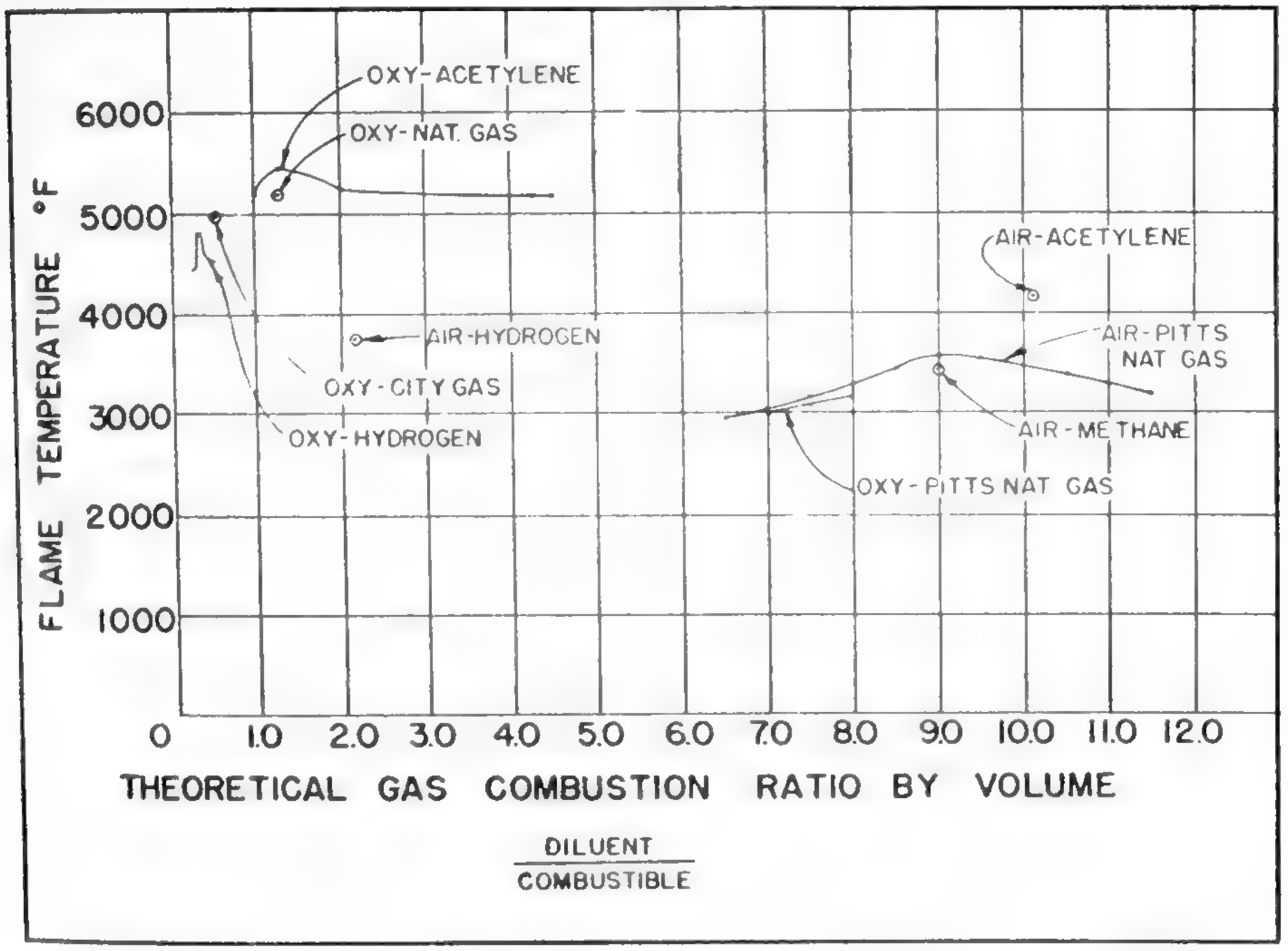


Fig. 3.—Variation of Flame Temperature with Variations of Gas Combustion Ratio

Oxygen

Oxygen in the gaseous state is colorless, odorless and tasteless. It is found nearly everywhere in nature. One of its chief sources is the atmosphere, which is composed of about 21% oxygen by volume.

The characteristic which makes oxygen all-important in gas welding and cutting is its ability to support combustion. Although there is sufficient oxygen in the air to support combustion, the use of pure oxygen speeds up reactions and increases flame temperatures.

Oxygen Preparation.—A substantial quantity of the oxygen used in industry is extracted from the atmosphere, which has the following chemical composition, by volume: Nitrogen, 78.03%; Oxygen, 20.99%; Argon, 0.94%; Carbon Dioxide, Hydrogen, Neon, Helium, etc., 0.04%.

In the extracting process, air is first compressed to about 3000 psi. (Some types of equipment operate at much lower maximum pressure.) It is then allowed to expand to a rather low pressure. In this latter step the air is substantially cooled and liquefaction occurs. The liquid air is then sprayed on a series of evaporating trays or plates in a so-called rectifying tower. The nitrogen and other gases in the liquid air boil at lower temperatures than the oxygen and as these gases escape from the top of the tower, high purity liquid oxygen remains in a receiving chamber at the base of the tower.

Oxygen can also be produced by heating mercuric oxide (HgO), barium oxide (BaO_2), potassium chlorate ($KClO_3$) and other compounds containing oxygen, and by the electrolysis of water. In the last mentioned process, an electric current is passed through water containing an electrolyte such as caustic soda, to increase the electrical conductivity. The water will decompose, the oxygen collecting at

the positive pole and the hydrogen at the negative pole.

Oxygen is distributed to the user as a compressed gas in individual cylinders or by one of several bulk distribution methods. In the individual cylinders the gas is usually under pressure of approximately 2000 psi. Cylinders of various capacities are used, holding in the neighborhood of 70, 80, 122, 244 and 300 cu. ft. of gas.

To satisfy the large consumption of some industries, gaseous oxygen may be transported from the producing plant to the user as a compressed gas in multicylinder portable banks or long high-pressure tubes mounted on truck trailers. These portable units are connected directly to a consumer's pipe-line distribution system and the tractor unit disconnected and used to return empty cylinders for refilling. The trailers may hold as much as 30,000 to 50,000 cu. ft. in the larger units, and 10,000 cu. ft. in the smaller units.

Another method of oxygen distribution is to transport the oxygen from the producing plant to the consumer as liquid oxygen. Insulated containers both on trucks and railroad tank cars are employed. At use points where consumption is high, the liquid oxygen is transferred to an insulated storage holder on the user's property, from which it is withdrawn, converted to gas, and passed into the distribution pipe lines by means of automatic equipment as needed. For users having medium-large consumption, the liquid oxygen is transported by truck, converted to a gas by equipment on the truck, and pumped under high pressure into storage tubes located on the user's property and permanently connected into his distribution piping system.

Safety Precautions.—Care must be taken that oxygen cylinders and fittings are kept away from oil and/or grease at all times. Also, oxygen cylinders should never be stored near highly combustible materials. The gas should never be used in pneumatic tools, to start internal combustion engines, to blow out pipes, to dust clothes or to create a pressure head in tanks. For further information see Chapter 46, Safe Practices in Welding and Cutting.

Gas Distribution in Plants

Gas is distributed to various sections of an industrial plant in single cylinders, by portable manifold or from stationary piped manifolds.

Single Cylinders.—For single welding and cutting torches consuming limited amounts of gas, the single cylinder will provide an adequate supply. A single cylinder is also extremely mobile and easy to handle. Trucks on which are mounted combinations of single oxygen and acetylene cylinders are now in universal use.

However, for equipment requiring higher rates of gas flow, individual cylinders are inadequate, particularly for continuous operation over long periods of time. Also, if the volumetric demand for acetylene is high, a single cylinder cannot be used, since acetone may be drawn from the cylinder along with the acetylene. It has therefore become standard practice to limit the withdrawal of acetylene from a single cylinder to an hourly rate not exceeding one-seventh of the cylinder's volumetric contents.

When using single cylinders, special care should be taken that they are not tipped over. Fastening the cylinders on a cylinder truck or securing them against a rigid support will aid considerably. All hose connections should be kept as short and free from sharp twists as possible.

Portable Manifolding.—When gases are required at a volumetric rate exceeding that which may be obtained from a single cylinder, two or more cylinders may be manifolded. Such an arrangement, called a portable manifold, connects the cylinders with a single, common, pressure-reducing regulator. This system provides a supply directly to the equipment to be used.

Stationary Manifolding.—Where very large volumes of gas are regularly required or where a centralized gas supply is desired, a stationary manifold may be installed. This type of manifold consists of an adequately supported, stationary, pipe-type header to which a number of cylinders are connected by means of *pigtails.* One or more permanently mounted regulators serve to reduce and regulate the pressure of the gas flowing from the manifold to the point or points of consumption. Such an arrangement is illustrated in Fig. 4.

Other Systems.—When stationary manifolds, truck trailers or liquid storage equipment is used as a source of oxygen in a consumer's plant the gas is distributed to the points of use by a pipe line.

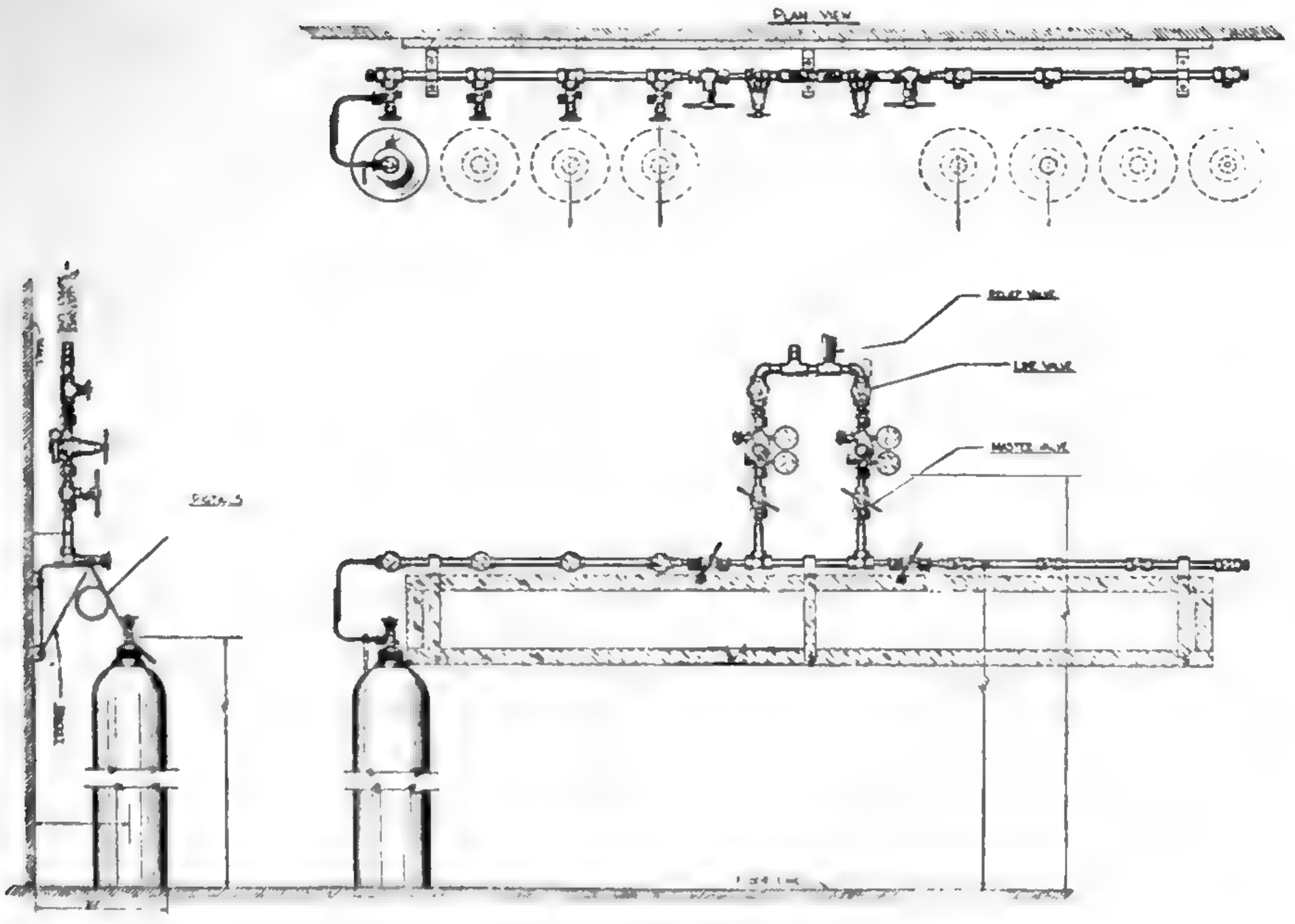


Fig. 4.—Gas Manifold

This pipe line must be properly designed to handle and distribute the gas to the points of use without undue pressure drop and to deliver the volumes required. Distribution pipe lines are installed in both large and small plants. The individuals using the gas are relieved of the work and bother of changing cylinders and there is ample, uninterrupted supply of gas at all times. Acetylene pipe lines usually parallel the oxygen lines.

Connections to the pipe line at points of use are made by suitably designed equipment. The oxygen line connection is fitted with a filter, a shutoff valve, and a regulator. The acetylene line connection is fitted with a shutoff valve, hydraulic back pressure valve, relief valve, a vent piped to the outdoors, and also a regulator. The acetylene hydraulic back pressure valve is a protective device which prevents flashbacks and backfires from entering the main pipe lines. Figure 5 illustrates a typical welding station layout.

Regulations and Safe Practices

When installing oxygen and acetylene manifolds and pipe lines, the regulations set forth by the National Board of Fire Underwriters should govern. The manifolds should, in all cases, be obtained from reliable manufacturers and installed by competent personnel, familiar with proper construction practices.

Briefly, these are the regulations governing acetylene manifolding:

1. Only cylinders containing gas at

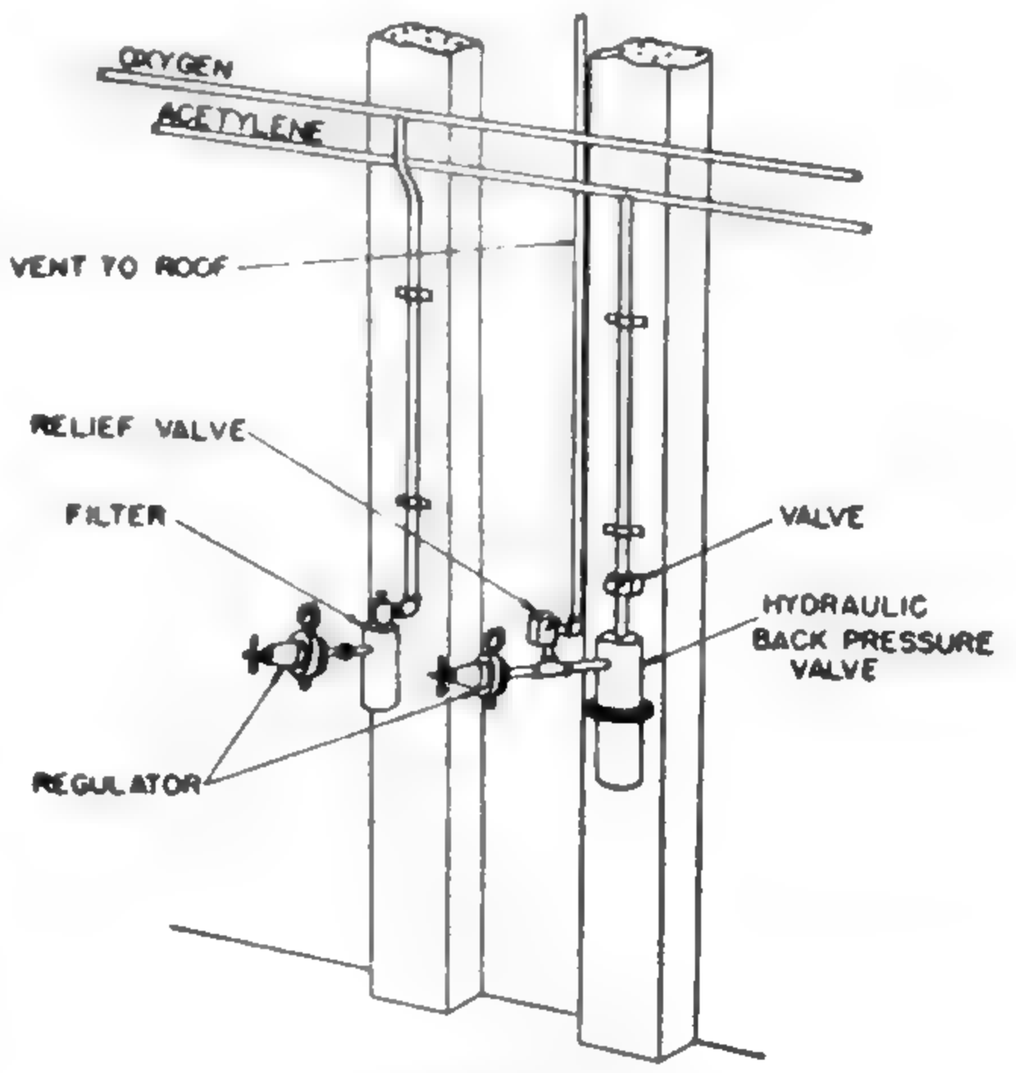


Fig. 5.—Welding Station for Pipe-Line Gas Supply

approximately equal pressures shall be manifolded.

2. Fuel gas cylinders connected to one manifold inside a building shall be limited to 2000 cu. ft. total volume.

3. The manifold header shall be constructed of double extra heavy steel pipe not exceeding $1^1/_4$ in. in diameter.

4. Water seals and shut-off valves must be properly located.

5. The pressure in the shop supply piping system shall not exceed 15 psi.

6. The manifold shall be subjected to a test pressure of 1000 psi. after assembly.

7. When a leak is suspected in an acetylene line, test using grease-free soap. Never use a flame to detect a leak.

Other rules of safety previously mentioned plus the safety rules suggested in Chapter 46 should be followed.

REGULATORS

Primarily, the functions of a regulator are: (1) to reduce the source pressure (from generator, cylinder, manifold or pipe line) to a workable pressure and (2) to maintain a constant delivery pressure and gas volumetric rate regardless of the pressure variations at the source. In addition, a regulator must permit adjustment to deliver gas at a certain desired pressure within its rated pressure range.

Regulators may be generally classified into four main types: the single-stage nozzle type, the single-stage stem type, the two-stage type, and the high-capacity, high-pressure line type.

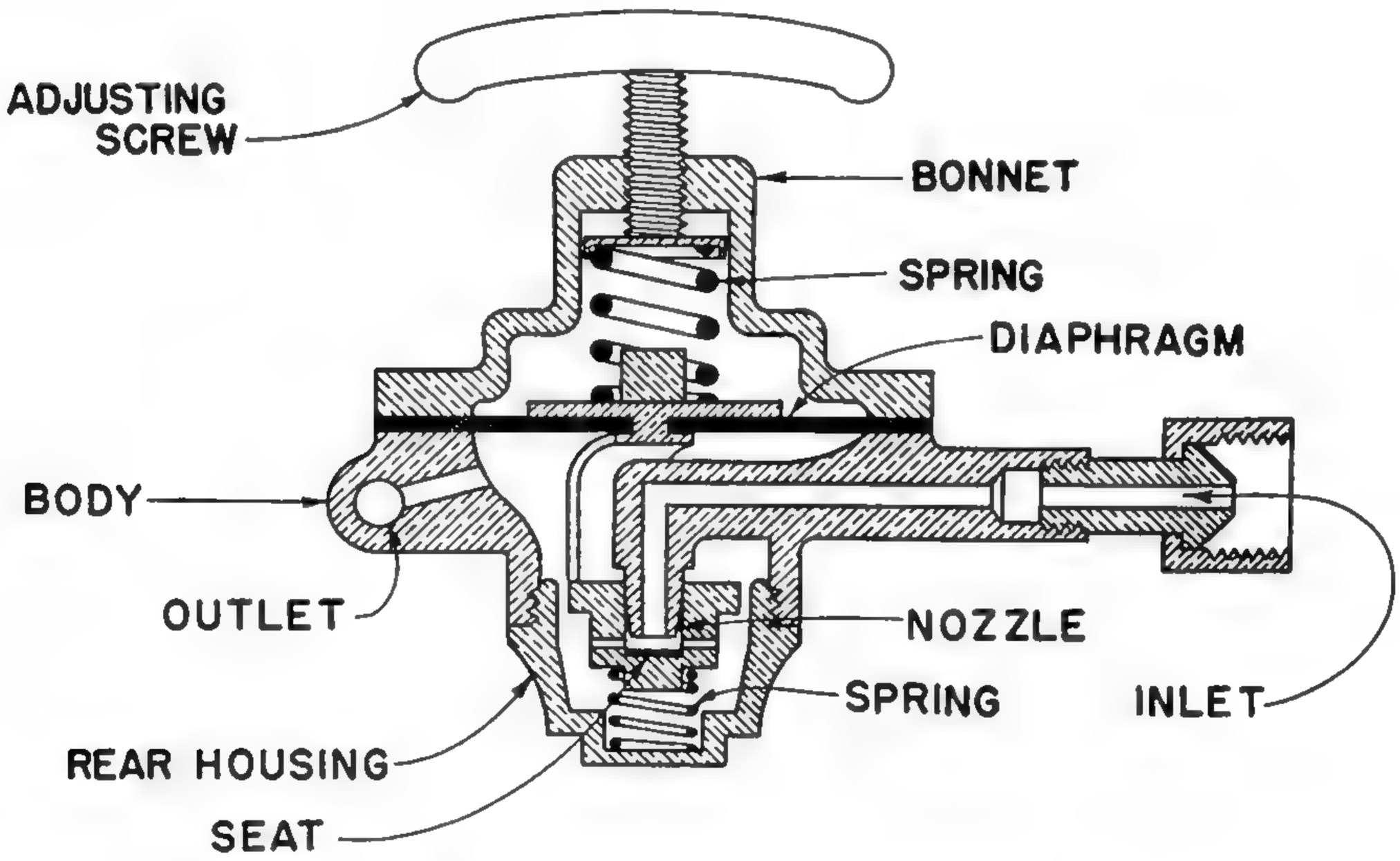


Fig. 6.—Single-Stage Nozzle-Type Regulator

Oxygen manifolds should be installed following these regulations:

1. All installations shall consist of nonferrous piping and fittings, preferably brass or copper.

2. Fittings may be either welded to the header or screwed using litharge and glycerine.

3. The assembly shall be capable of withstanding a test pressure of 3000 psi.

4. Oxygen manifolds shall not be located in acetylene generator rooms or in rooms where combustible gases are present.

5. Again, oxygen cylinders, fittings and regulators must be kept free of oil and/or grease.

Nozzle-Type Regulator

A single-stage nozzle type regulator is shown schematically in Fig. 6. It consists essentially of a brass casing, an adjusting screw, suitable springs, a diaphragm, a nozzle and a seat. When the adjusting screw is turned counterclockwise until it is free, the seat is forced by spring action against the nozzle, closing it. All gas flow is thus stopped. As the adjusting screw is turned clockwise, the seat is forced away from the nozzle letting the

gas from the cylinder enter the outer body chamber. This increases the pressure on the diaphragm which forces the seat closer to the nozzle. By thus maintaining a balance of spring pressure and gas pressure on the diaphragm, the desired outlet pressure can be set and held.

Stem-Type Regulator

A single-stage stem-type regulator operates like the nozzle type, with one exception. Referring to the schematic drawing in Fig. 7, it will be noted that the high inlet pressure operates to hold the seat against the nozzle instead of away from it, as in the nozzle type. Aside from this difference, the nozzle and stem types operate and are adjusted in a like manner.

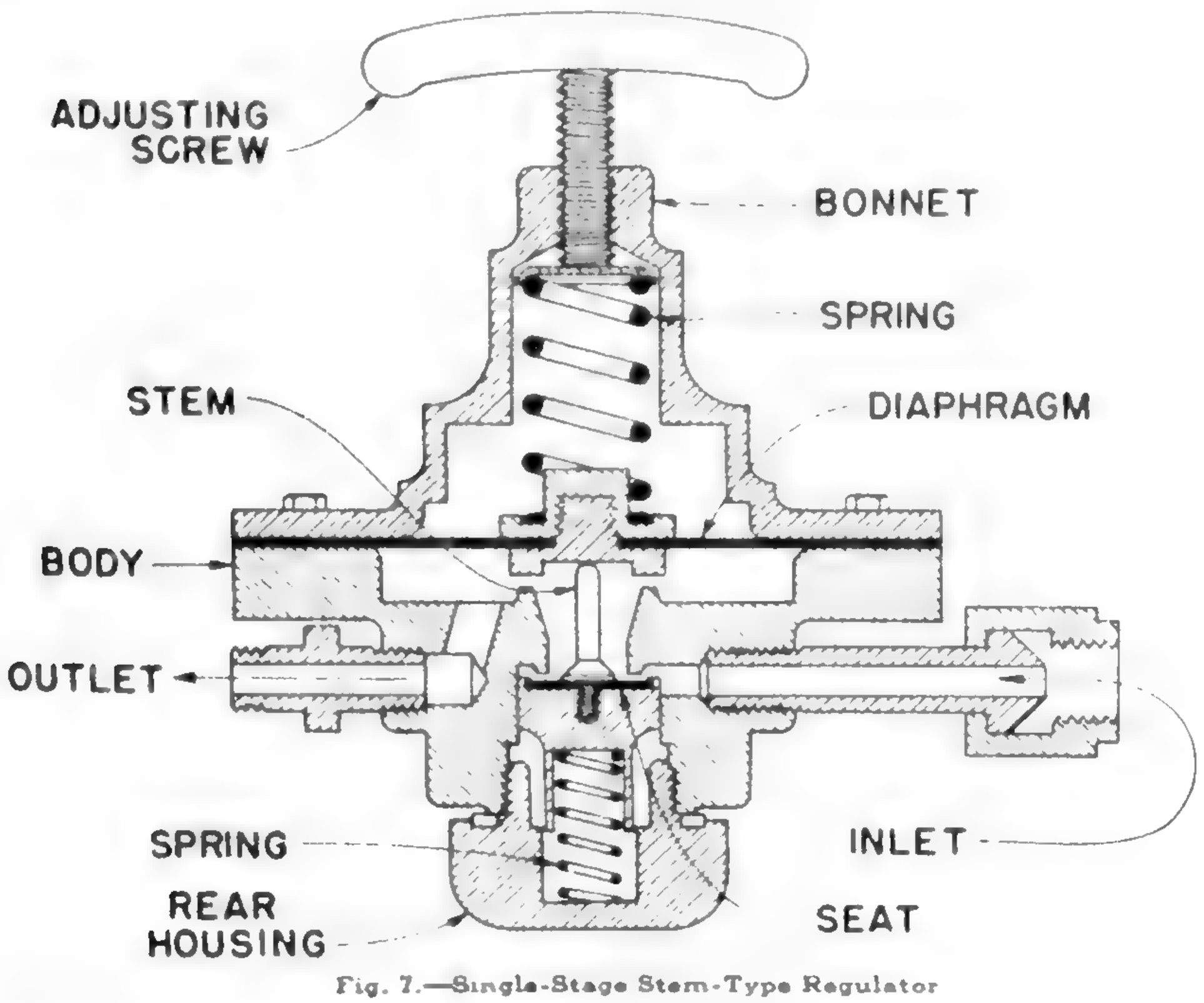


Fig. 7.—Single-Stage Stem-Type Regulator

Two-Stage Regulator

The nozzle and stem type regulators both accomplish a reduction of the gas pressure in a single stage. In the two-stage regulator this reduction is done, as the name implies, in two stages. The high pressure gas initially passes through a generally non-adjustable nozzle or stem-type assembly. This assembly, equipped with an extra-heavy diaphragm and spring complement, reduces the pressure to an intermediate value. Further pressure reduction is accomplished by passing the gas through a second assembly of either a stem or nozzle type. This latter stage may be adjusted to give the desired outlet pressure. By using such a dual arrangement, a more constant delivery pressure than that of a single-stage unit is insured. The two-stage regulator will give practically constant delivery pressure from a full cylinder down to an empty one.

In addition to the stem-nozzle combinations of two-stage regulators, there are also two-stage regulators manufactured using two stem-type regulators or two nozzle-type regulators in series. The high pressure gas is dropped to working pressure in two steps. Thus, the tendency of the nozzle-type regulator pressure to decrease (or the stem type to climb) is lessened and a more constant outlet pressure is maintained.

A typical two-stage regulator is shown in Fig. 8, which shows the principal parts that go into its assembly. The sketch

shown is schematic and physically, looks quite different. In this regulator the nozzle type assembly is shown as the initial stage; other regulators would have a stem-type assembly as the initial stage. Although both stages are adjustable, once the first stage has been set for a particular operation, it usually is not changed; the second stage is readily adjustable like a single-stage regulator.

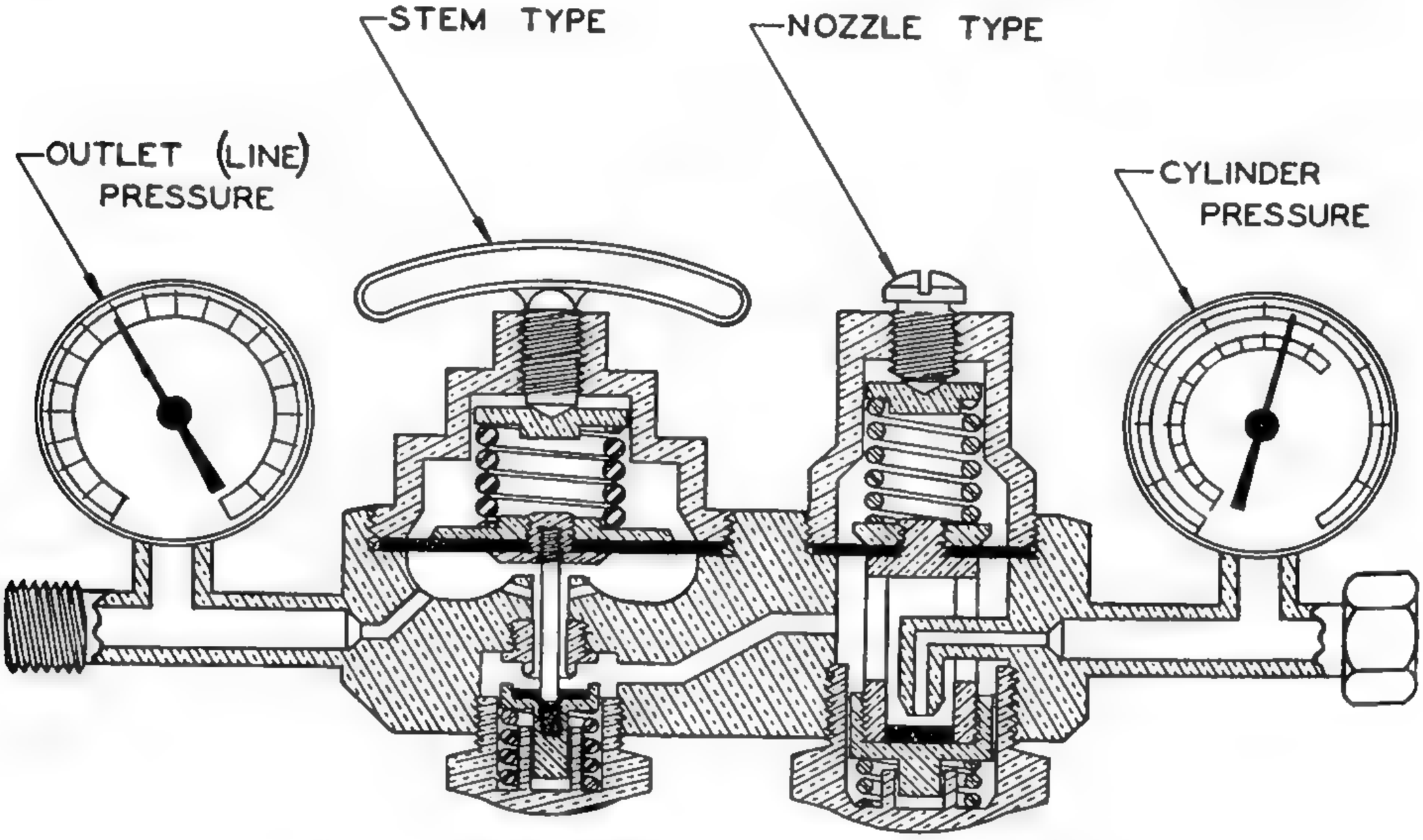


Fig. 8.—Two-Stage Stem- and Nozzle-Type Regulator

Generally, each of the above types of regulators has a union nipple and nut for attaching it to the cylinder, while the outlet side has a standard hose connection. Generally, there are two gages per regulator, one of which shows the pressure in the cylinder while the other gives the delivery pressure. Most regulators also have a device for protecting the seat from the heat generated by the compression of the gas inside the regulator. This device may vary widely in design among various makes of regulators, but has the general function of serving as a conductor for removing the heat generated in the vicinity of the seat. Except for these similarities, regulators may vary greatly in detail and physical appearance.

High-Capacity Regulator

For extremely high-pressure and high-capacity conditions, reducing regulators employing gas or spring preloaded diaphragms have been developed. These operate using principles similar to those of the types discussed above but are constructed for heavier duty.

High capacity regulators which operate from low-source pressures, such as would be found in acetylene generators, are also available. Regulators designed for controlling outlet pressures where the source is a relatively low-pressure, liquid oxygen container also may have large capacities.

Line or station regulators, such as are used for controlling outlet pressures from pipe distribution systems, may also pass large volumes.

Regulator Operation

The various types of regulators have operational characteristics as shown in Fig. 9. Here the operations show that, if the flowing pressure is initially set at some chosen value, and gas is withdrawn through the regulator without the adjusting screw setting being changed, then the outlet or supply pressure to the torch will vary as follows:

In a *nozzle-type* regulator the outlet pressure will gradually decrease, as the cylinder pressure decreases.

In a *stem-type* regulator the outlet pressure will gradually increase, as the cylinder pressure decreases.

In a *two-stage type* regulator the outlet pressure will be maintained through prac-

tically the whole range of cylinder pressures.

The reasons for the above behavior of regulators involves finally obtaining a dynamic force balance between the cylinder gas pressure on the seat, the compensating spring pressure, the gas pressure on the diaphragm and the adjusting screw spring pressure. These resultant forces, although of a relatively simple nature when taken individually, present a rather complicated picture when taken as a whole. A discussion of them, therefore, is not included here.

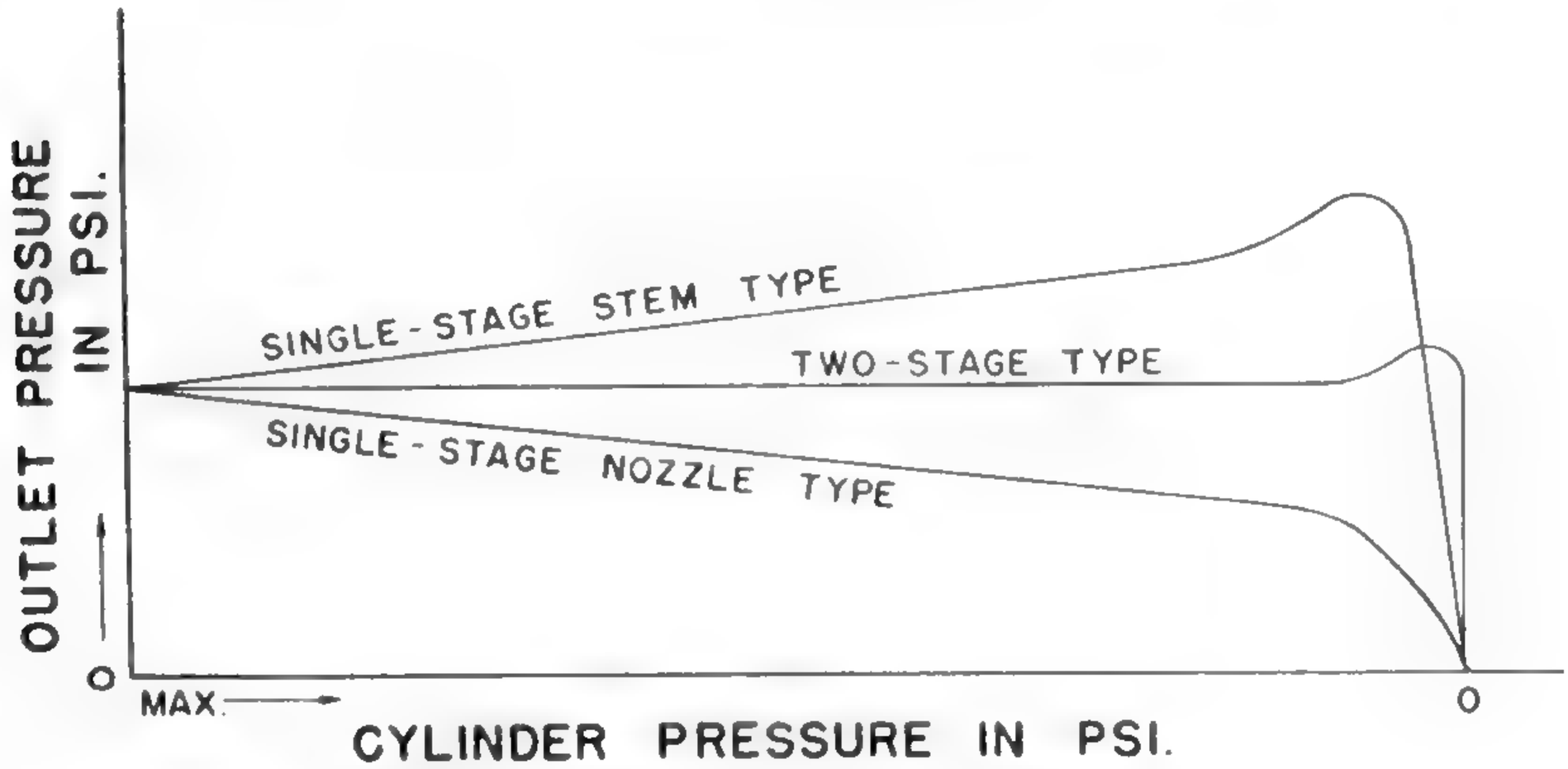


Fig. 9.—Operating Characteristics of Regulators

Cylinder and Hose Connections

To guard against forming explosive mixtures of oxygen and acetylene by an interchange of acetylene and oxygen regulators, these regulators are manufactured with different-sized cylinder nuts. The oxygen cylinder nut has a thread pitch diameter of approximately 0.903 in. with 14 threads to the inch, right hand. The acetylene cylinder nut thread has an 0.855 in. pitch diameter with 14 threads to the inch, left hand. The regulator outlet fittings also differ, oxygen fittings having a right-hand thread while the acetylene and other fuel gas fittings have left-hand outlet threads.

Safety Rules

The following safety precautions should be observed when dealing with regulators:

1. Regulator gages should be checked periodically to assure that their readings are true readings.
2. Adjusting screws should be turned in slowly to protect the regulator diaphragm from injury by a sudden surge of high pressure gas.
3. Regulators should be repaired only by the supplier or by skilled mechanics properly trained in the work.
4. Regulators should never come in contact with oil or grease.
5. Cylinder nuts and outlet fittings should be checked periodically to detect faulty seating.
6. Regulators should be connected to the cylinder valves using the correct size wrench. Connections should never be forced.
7. If leaks are suspected, testing should be done using a soapy water solution.
8. The regulator adjusting screw should be released (turned counterclockwise until it is loose) before the cylinder valve is opened.
9. When regulators are to be out of service for periods of several weeks, their adjusting screws should be turned in just enough to relieve the pressure on the internal valve seat.

TORCHES AND TIPS

Welding Torches

The gases, having been reduced in pressure in passing through the gas regulators, are fed through suitable rubber hoses to a welding torch. The welding torch is a device used for mixing and controlling the flow of gases to the tip. It also provides a means of holding and directing the tip. In Fig. 10 is shown a simplified schematic drawing of the basic elements of a welding torch. There are

two throttling or control valves, usually at the back or butt end of the torch. The gases, after passing the valves, flow through metal tubes inside the metal handle and are directed together by the gas mixer at the front end (see Gas Mixers). The tip is shown as a simple tube, narrowed down at the front end to produce a suitable welding cone.

On all torches, the fuel-gas hose fitting has a left-hand thread, making it possible to screw on only the left-hand hose nuts used on fuel gas hose. The other fitting, to be used for oxygen, has a right-hand thread.

There is no restrictive limit on the oxygen pressure, however. It can, and sometimes does, range up to 25 psi. on the larger sizes of tips, when used in positive pressure torches.

The injector type (or low pressure) operates at an acetylene pressure of less than 1 psi. (a pressure which can be easily supplied by the low-pressure type of acetylene generator). Oxygen, on the other hand, is supplied at a pressure ranging from 10 to 40 psi., necessarily increasing as the tip size is increased. As described under Gas Mixers, this oxygen acts to aspirate or draw in the acetylene

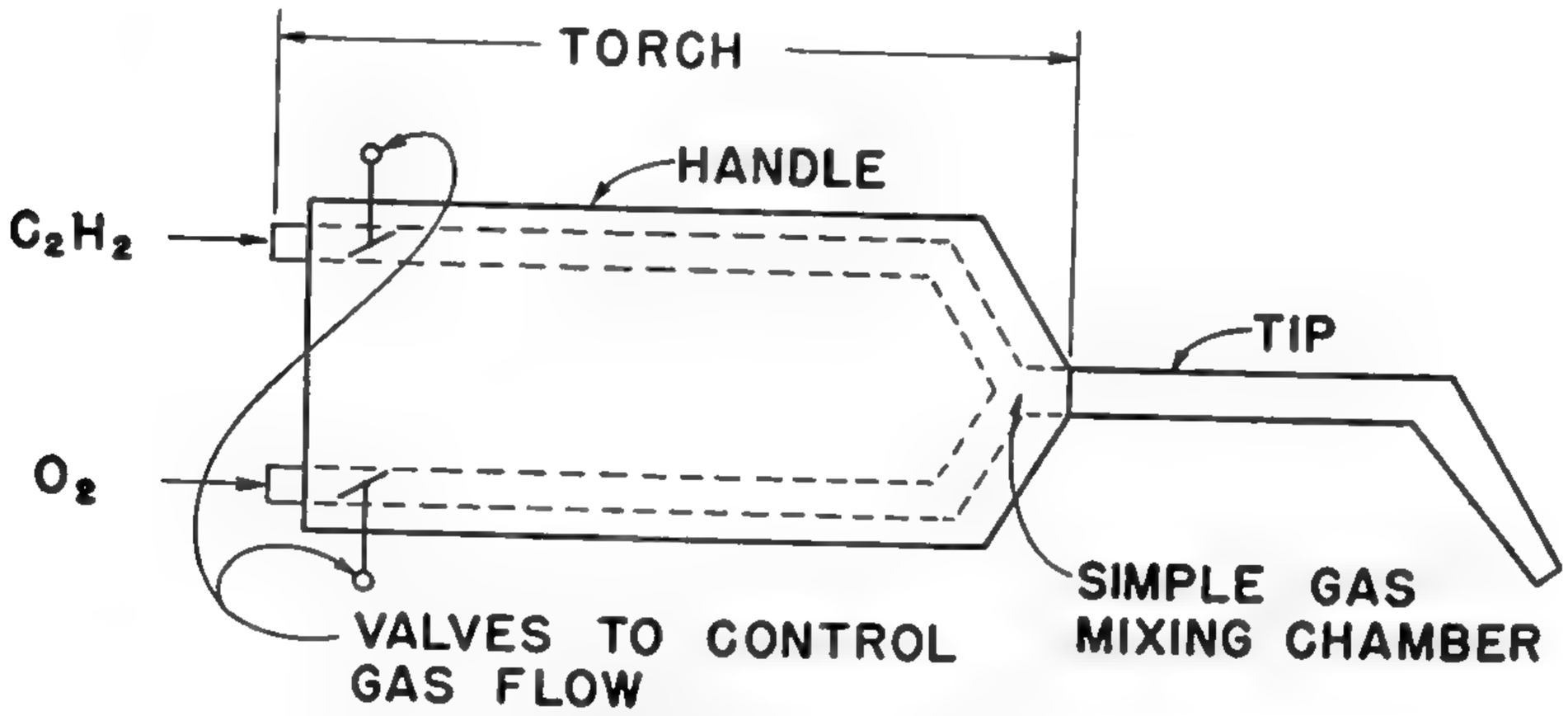


Fig. 10.—Basic Elements of a Welding Torch

Modern torches are manufactured in a variety of sizes ranging from the small torch for extremely light (low gas flow) work to the extra heavy torches (high gas flow) used generally for localized heating operations. A typical small welding torch used for sheet metal and aircraft welding will pass acetylene at volumetric rates ranging from 1/4 to 35 cu. ft. per hr. The medium sized torch is designed to provide for acetylene flows from one to 100 cu. ft. per hr. Heavy-duty heating torches may provide for acetylene flows as high as 400 cu. ft. per hr.

Types of Torches

There are two general classes of torches: the positive- or equal-pressure type and the injector type. The positive-pressure type torch (also called medium pressure) requires that gases be delivered to the torch at pressures generally above 1 psi. gage. In the case of acetylene, the pressure must necessarily be between 1 and 15 psi., while oxygen generally is supplied at approximately the same pressure.

and mix with it before both gases pass into the tip.

Care of Torches

As is shown in Fig. 11, each welding torch either has a gas mixer unit as an integral part of the torch or provision is made to attach a mixer by screwing it onto the front end of the torch. In either case, the welding tip must be screwed into place. This means that the front portion of a welding torch must not be mishandled or difficulty will be experienced in securing a perfect gas seal. In those torches that permit various sizes of mixers to be attached to the front end of the torch, particular care should be exercised not to score the seating surfaces. Slight damage of these seating surfaces will cause gas leaks and consequent frequent popping; escaping acetylene may also burn at the leak. The necessity for this care is apparent when the utility and function of the gas mixer is better understood.

Even though welding torches are built

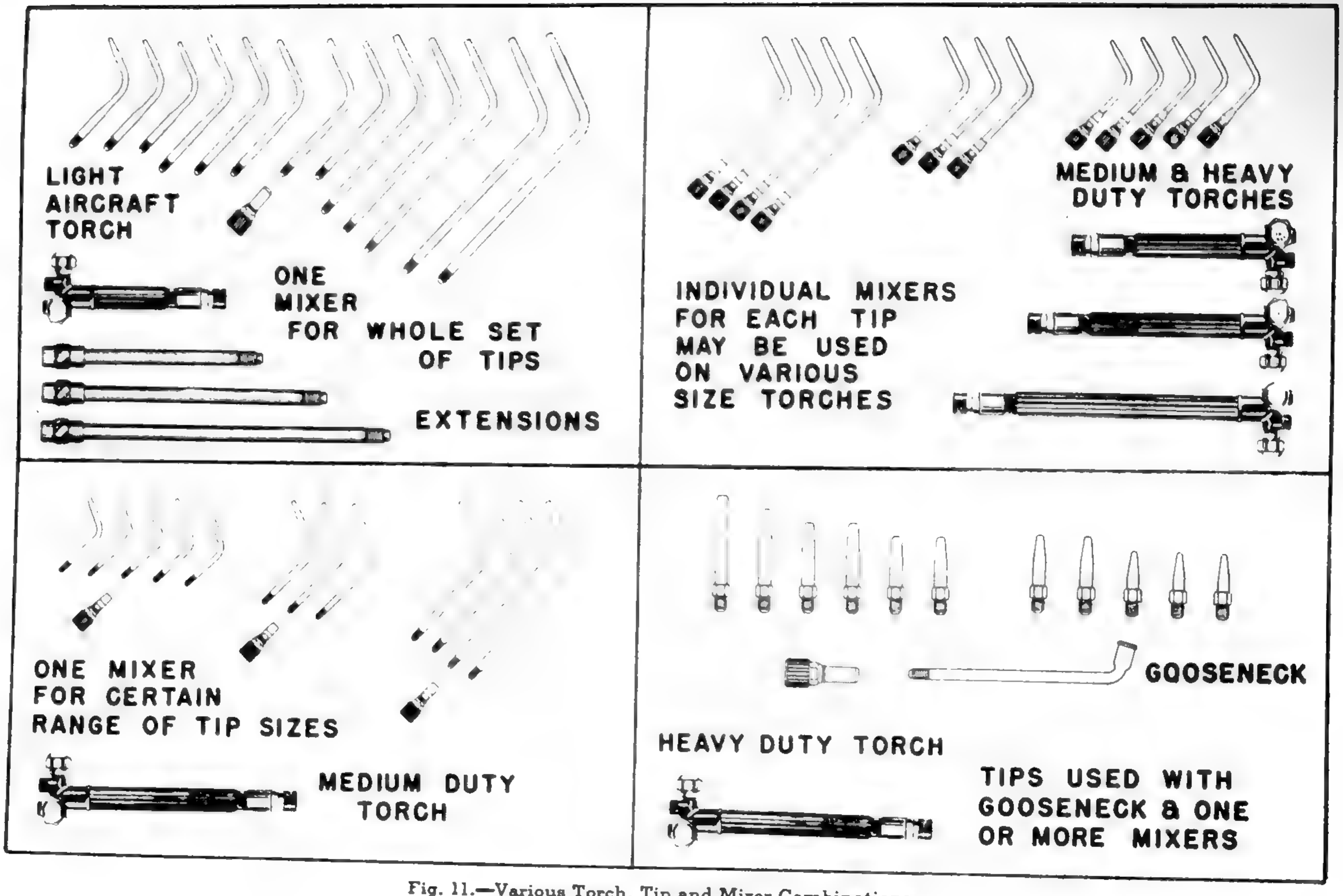


Fig. 11.—Various Torch, Tip and Mixer Combinations

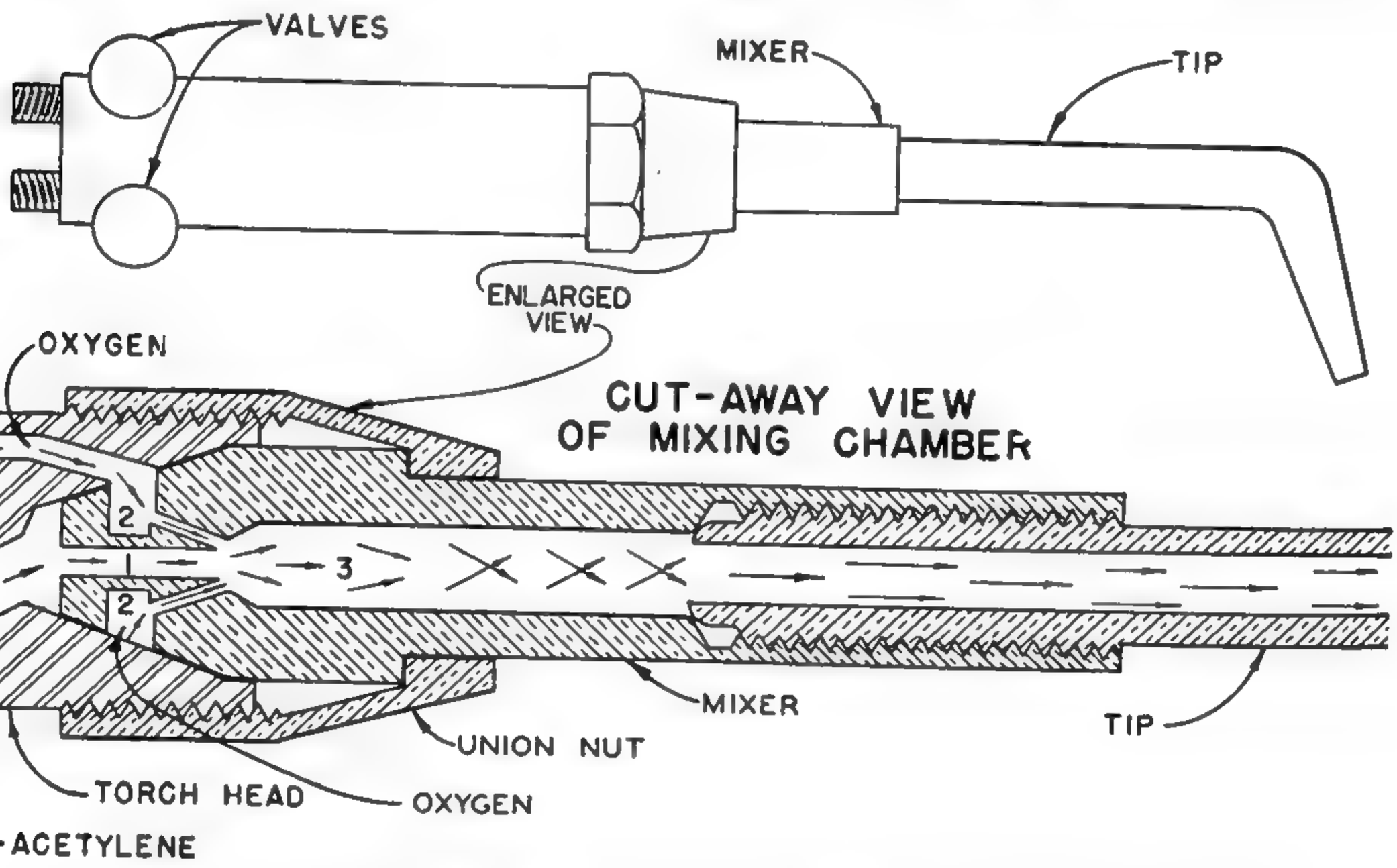
to withstand rough usage, the following rules should be kept in mind when handling them:

1. Keep torches away from all oil and grease.
2. Never use a wrench to tighten the torch valves.
3. Never clamp the torch handle tightly in a vise as this may collapse the handle and injure the gas tubes inside.
4. Keep the mixer seat free of dust and other foreign matter at all times.
5. Before using a torch for the first time, check the packing nut on the valves to insure that the nut is tight. Some manufacturers ship torches with these nuts loose.

automobile carburetor which mixes air and gasoline vapor. A well-designed gas mixing chamber, or gas mixer, must be able to perform well all of the following essential functions:

1. Mix gases thoroughly for proper combustion.
2. Arrest flash-backs that might occur through improper operation.
3. Stop any flame from traveling farther back than the mixer.
4. In some designs, permit a range of tip sizes to be operated by the one size of mixer.

Figure 12 shows a view of one type of a positive pressure mixer. The two gases have already been controlled as to volu-



THE TWO GASES ARE FED IN AT POINTS 1 (ACETYLENE) AND 2 (OXYGEN), THERE BEING A MULTIPLICITY OF HOLES FOR THE LATTER. THE GASES ARE MIXED, BEGINNING AT POINT 3, THROUGHOUT THE MIXING CHAMBER, AS SHOWN BY THE VARIOUS ARROWS.

Fig. 12.—Basic Elements of a Positive Pressure-Type Welding Torch Mixer

Gas Mixers

The basic view of a torch shown in Fig. 10 illustrates a mixing chamber as being simply that section of a torch where acetylene and oxygen come together prior to passing into the welding tip proper. This illustration is valid as the mixing chamber is defined as "that part of a gas welding or cutting torch wherein the gases are mixed for proper combustion at the tip end." In this respect, the action of the mixing chamber is similar to an

metric rate by the throttling or adjusting valves. Acetylene enters through orifice *1*, while the oxygen enters at orifice *2*. There are usually several holes for one of the gases, to provide for better mixing, and to act as a deterrent to any flash-backs that might be initiated at the end of the welding tip. The gas in the annular chamber that feeds all holes marked *2* must be at a pressure high enough to insure the proper volumetric gas flow into chamber *3*. It can be seen that the pres-

sure gradient of the gas along paths 2 would tend to prevent any flame from proceeding back upstream along this path of gas flow. This is more clearly brought out in Fig. 13 which shows a typical gas pressure gradient existing across a torch and tip combination. Here again it can be seen that the gas pressure decreases as the gas proceeds downstream.

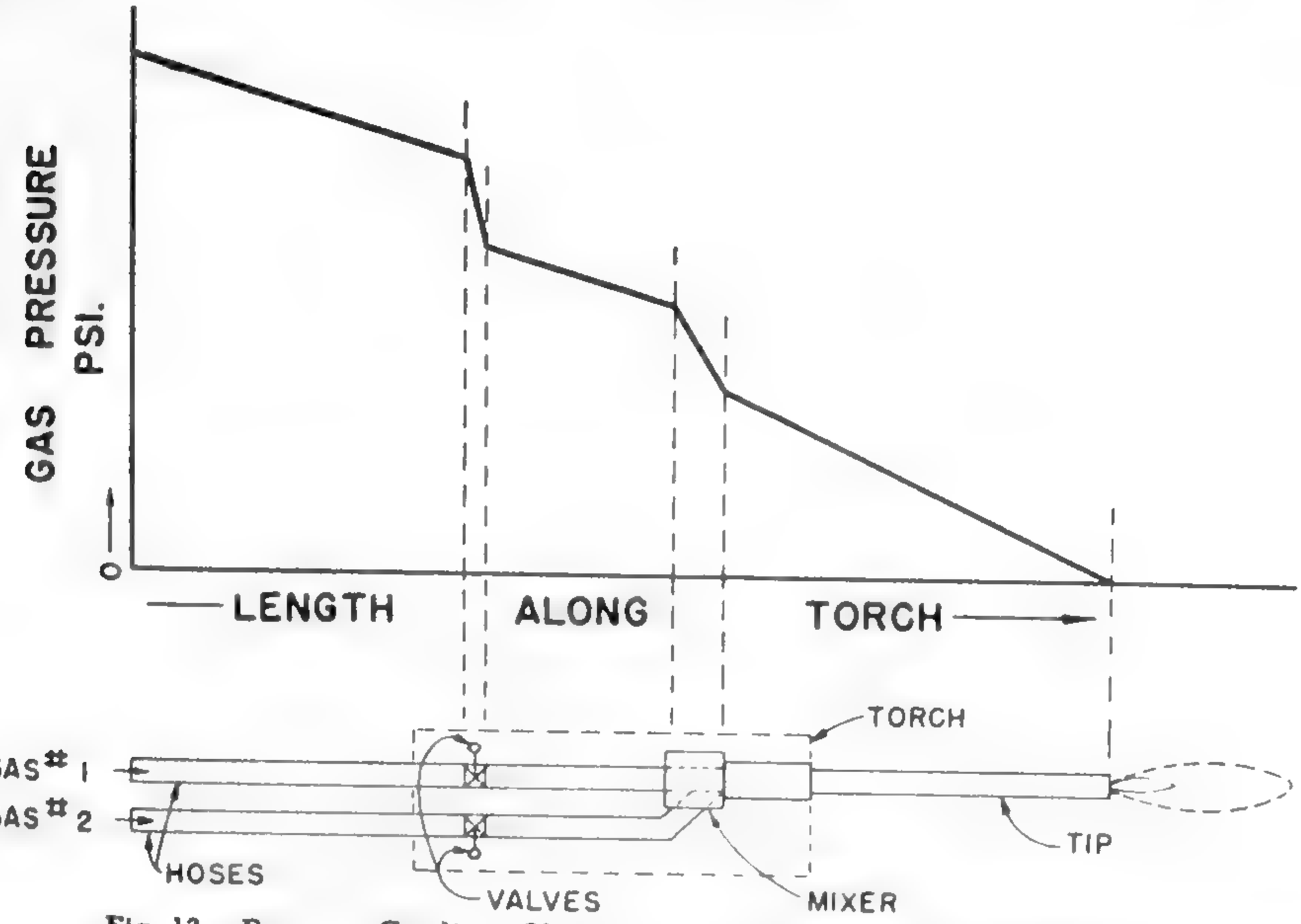


Fig. 13.—Pressure Gradient Along a Torch, Mixer and Tip Combination

A typical injector type of gas mixer shown in Fig. 14 is similar to the positive pressure type shown in Fig. 12. The main difference in operation is that the acetylene is at a pressure of 1 psi. gage or lower, while the oxygen pressure may be from 10 to 40 psi gage. The injector is so designed that as the oxygen emerges from hole *1* into venturi chamber *3*, it creates a vacuum, which aspirates or sucks the proper volume of acetylene into the gas mixture from the annular chamber *2*. A comparative study of Figs. 12 and 14 will greatly clarify the differences of construction between the two types of mixers.

Welding Tips

The welding tip is that portion of the welding apparatus through which the gases pass just prior to their ignition and burning. It enables the operator to guide the flame and direct it to the work with greater ease than would otherwise be possible.

Tips are generally made of a nonferrous metal such as copper, or a copper alloy. Such materials have high thermal conductivity, and their use reduces the danger of burning the tip at high temperatures.

Tips are manufactured mainly by drilling bar stock to the proper orifice size or by swaging tubing to the proper diameter over a mandrel. In either case, the bore size must be smooth to produce the required flame cone. The front end of the tip must likewise be shaped to permit easy use and provide a clear view of the welding operation being performed.

As is shown in Fig. 11, there is a great variety of welding tips, both as to size, shape and construction. As is also shown in that figure, there are two general methods of using tip and mixer combinations. One class employs a tip and mixer unit, which provides the proper mixer for each size of tip, thus insuring the most efficient combustion of the gases and the greatest heating efficiency. The other general class is that which employs either one or a few mixers for the entire range of tip sizes. In this case, the tip unscrews from its mixer, each size of mixer having a particular thread size to

prevent improper grouping of a tip and mixer.

For some classes of welding, a single mixer and a so-called gooseneck into which the various sizes of tips may be screwed are preferred.

Since tips generally are made of copper or a copper alloy, relatively soft materials, care must be taken to guard them against damage. The following precautions should be heeded:

1. Tips should be cleaned using tip cleaners designed for this purpose.
2. Tips should never be used for moving or holding the work.
3. Tip seat and/or threads always should be absolutely clean and free from foreign matter to prevent scoring when tightening the tip nut.

This would insure that the minimum range of one would be slightly less than the maximum range of the next smaller size. That this method of spacing welding tips is the simplest and most logical is rather obvious, but it does not take into account other factors that are of importance. These latter factors will be discussed subsequently.

Volumetric Rate of Flow of Acetylene.—It is not enough to simply determine that a given size of welding tip will pass some predetermined maximum volume of acetylene as a criterion of that tip's ability to weld. It would be possible to take any reasonably straight tubing of the proper diameter and, by supplying it with the required volumetric rates of acetylene and oxygen, find that the mixture burned

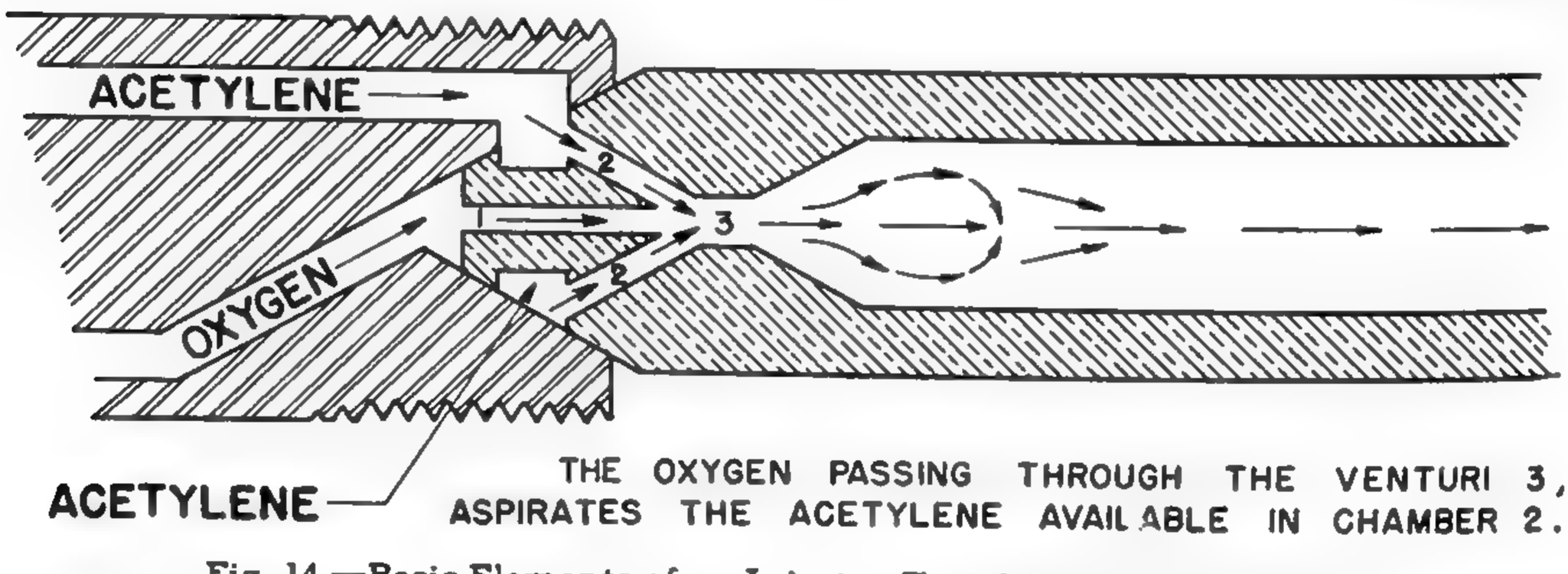


Fig. 14.—Basic Elements of an Injector-Type Welding Torch Mixer

When performing a welding operation, care must also be taken to obtain the correct flame adjustment. Improper flame characteristics will nullify correct torch, mixer and tip selection. Refer to Chapter 5 for detailed information on the proper methods for obtaining the desired flame characteristics.

Tip Sizes.—There should always be some logical relationship between the sizes of welding tips and the metal thicknesses. This relationship cannot be developed from fundamental physical laws but is empirical and has been determined by practical applications. By plotting thickness of steel that can be successfully welded against tip size (expressed in orifice cross-sectional area), a linear relationship between them is seen to exist. This is shown in Fig. 15. It will be seen that a so-called series of welding tips may be spaced by simply choosing them in such a manner that the metal thickness range covered by one overlaps slightly the range covered by the next tip size. at the end of the tubing. Assuming that the cone shape appeared satisfactory, the tip might still be unsatisfactory for actual welding even though it was employed on the proper thickness of metal. The important tests at this point would be to determine whether the action of the flame on the metal was too violent and had the effect of blowing the metal out of the molten pool. If the flame produced by the embryo tip was too harsh, it would be necessary to decrease the volumetric rate of acetylene (and also oxygen, as the flame is presumed to be maintained at a neutral condition) until the metal under test could be welded. Obviously, this flow rate would then be the maximum volumetric rate of welding acetylene that could be handled easily by this size of welding tip. As a general rule, the larger the volumetric rate of acetylene that may be handled by a specific size of tip, the more heat that tip is capable of producing. It may be mentioned here that the flame may be too soft for easy welding as

well as too harsh. The gas volumetric rates would then have to be increased.

Up to this point, no direct mention has been made of the heat produced by a tip, although to drive heat into metal at high temperature is the prime objective of any well-designed welding tip. Assuming that the combustion efficiency of most flame cones is reasonably high, the volumetric rate of welding acetylene becomes a measurement of the efficacy of a welding tip. It must be understood that the maximum useful volumetric rate of acetylene in welding is not the maximum volumetric rate that may be passed by a specific size of tip. This latter value is usually a good deal higher and depends to a large extent upon the condition of the lip of the tip. If the tip end has been slightly counterbored, the flame cone tends to remain on the end at higher acetylene volumetric rates, assuming that an acceptable straight cone is being produced. It is rather easy to pass even much higher flow rates by simply making a slight nick at the edge of the tip. This has the tendency to produce a distorted unsymmetrical cone shape.

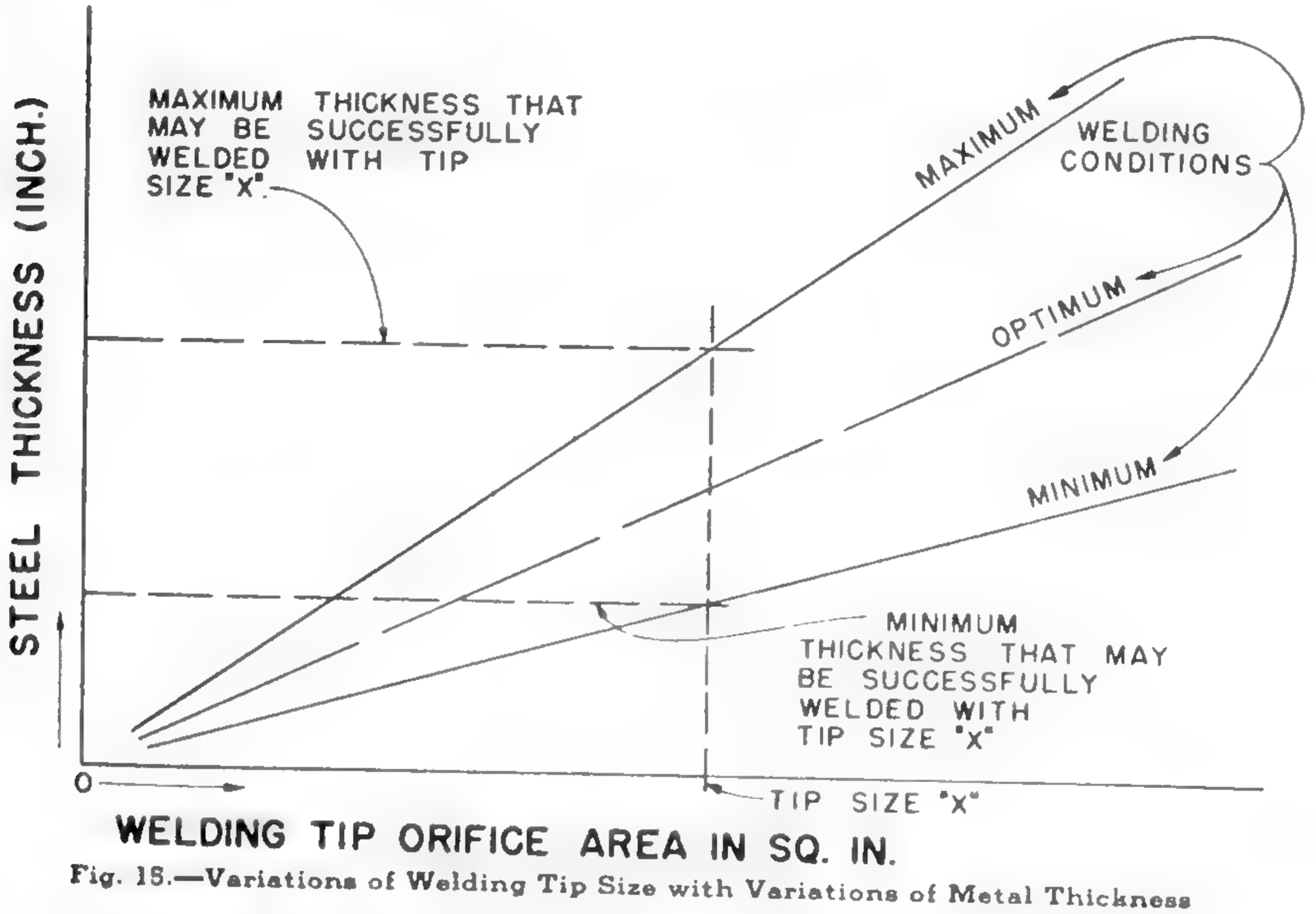


Fig. 15.—Variations of Welding Tip Size with Variations of Metal Thickness

Flame Cones

The prime objective of a welding flame is to raise the temperature of metal to the point where the metal can be welded. This can be most easily accomplished when the welding tip used produces a welding flame (or cone) that permits the heat to be easily directed. Consequently, as the other necessary conditions of usability of the welding tip are usually designed into it, the criterion of cone characteristics becomes an important one. Laminar or streamlined flow becomes of paramount importance throughout the length of the tip and especially so during the final run or front portion of the tip. A high velocity flame cone presents striking proof of the velocity gradient extending across a circular orifice when the existing flow is laminar. This is represented graphically in Fig. 16. This figure shows that since the greatest velocity exists at the center of the stream, the flame length at the center is likewise the greatest. In a like manner, since the velocity of the gas stream is lowest at the walls of the tip (bore) where the flowing friction is greatest, that portion of the flame bordering the wall is also the shortest. The foregoing is a reasonably complete and accurate description accounting for the shape of the cone, but a strict explanation would require a consideration of flame velocity, combustion and other factors.

From an analysis of the principles that underlie the formation of a flame cone, it

becomes possible to understand the flow conditions that exist along the last portion of the gas passageway in a tip. The shape of the flame cones will depend upon the smoothness of bore, the ratio of lead-in to final run diameter, the sharpness of neck-down, etc. These factors all affect the cone shape, producing a range of shapes illustrated in Fig. 17.

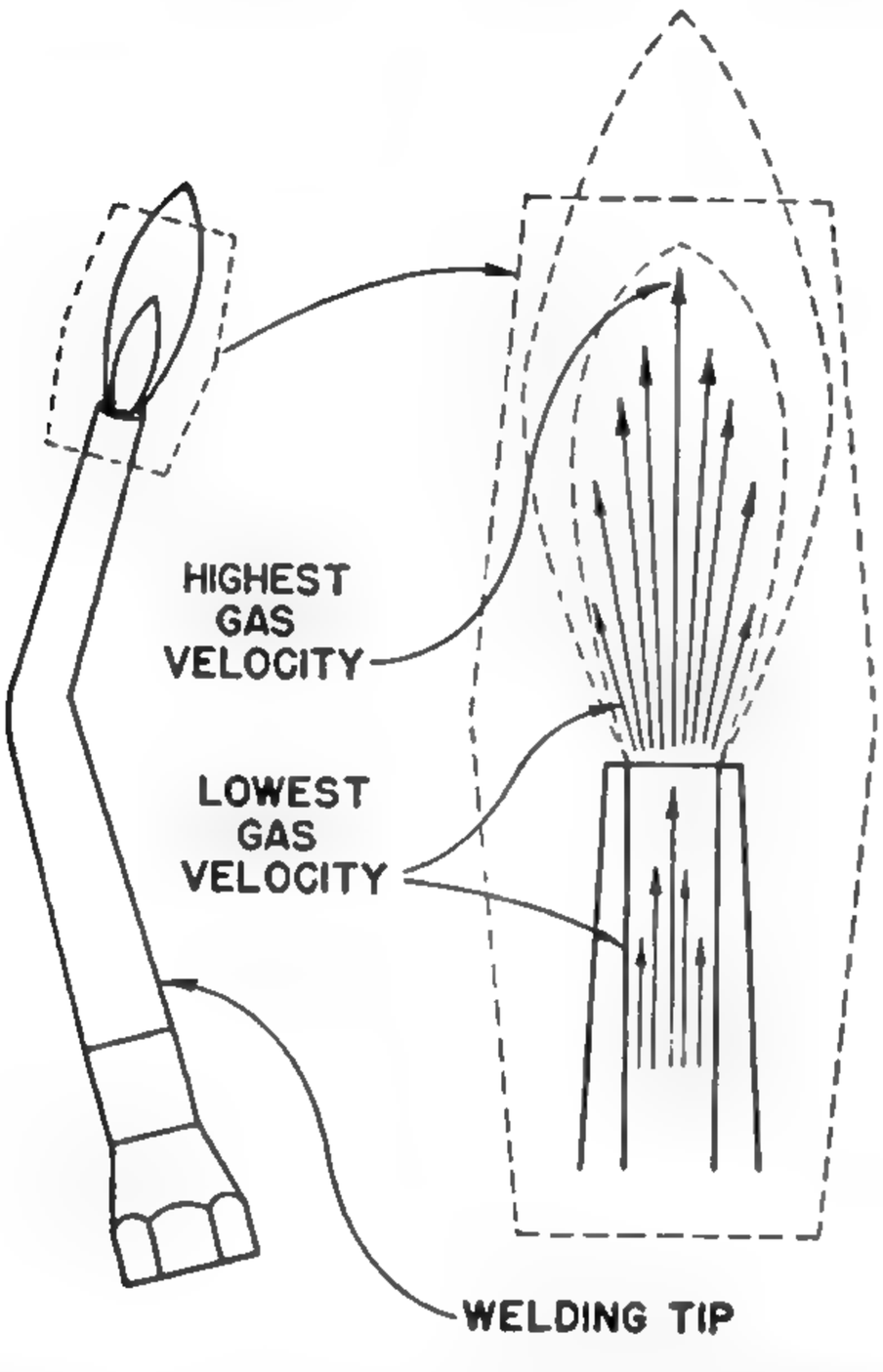


Fig. 16.—Vector Representation of Laminar Flow in a Welding Torch Tip

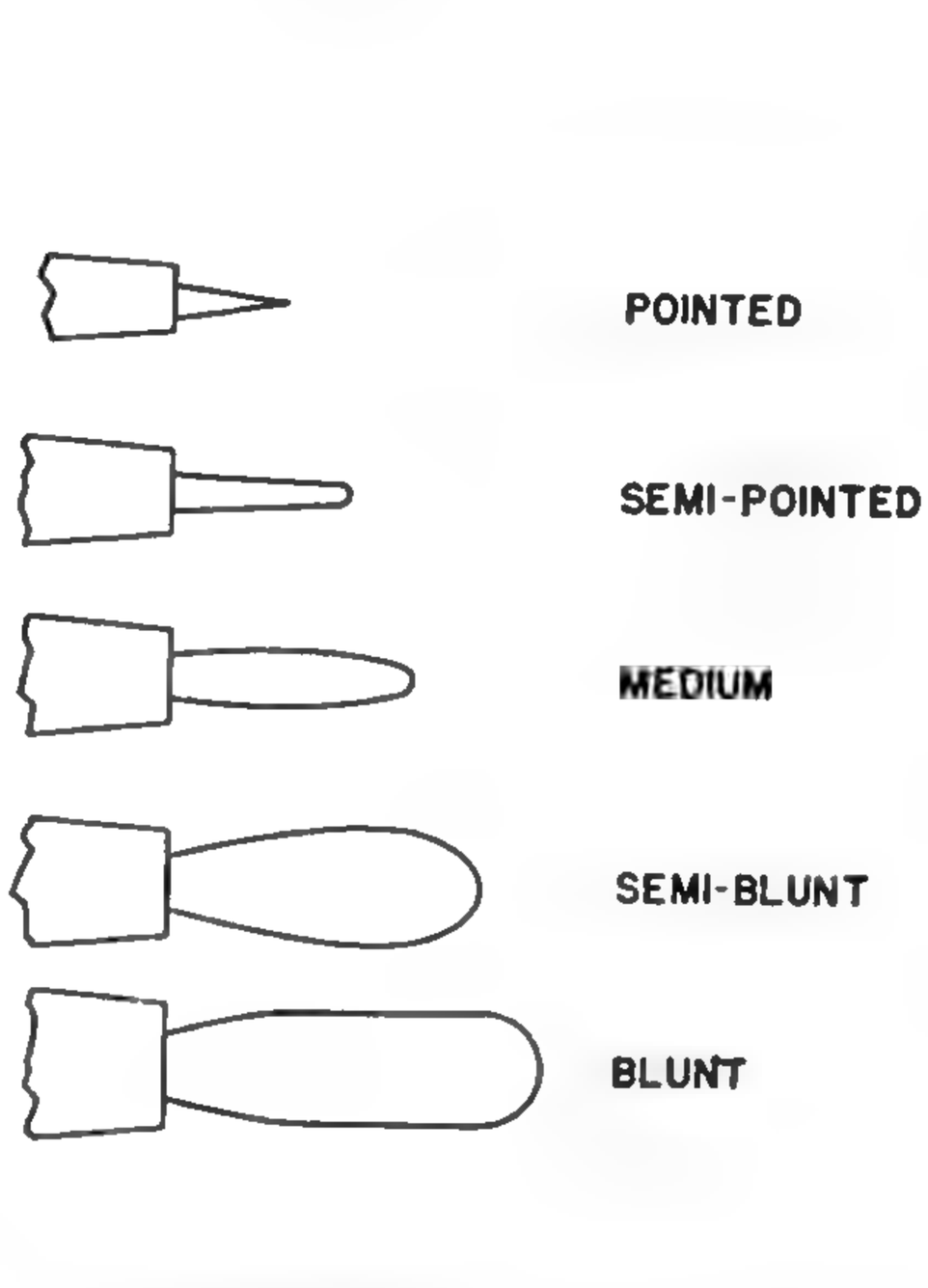


Fig. 17.—Representative Cone Shapes Produced by Welding and Heating Tips

AUTOMATIC GAS WELDING EQUIPMENT

A special type of gas burner is used in the automatic welding of strip stock to form welded tubing. This burner usually has orifices arranged in a straight line and performs the operations of preheating and final welding by applying heat at the longitudinal seam. There are many forms of such burners, depending upon the thickness of steel to be welded and the rate of welding desired. In addition, many types of special burners have been built to perform various simple heating operations and also heating in combination with metal forming and closing operations.

In all these operations, it is usually necessary to design a special heating burner that will fit the contour of the piece and provide the proper distribution of heat as desired. The torches supplying these burners are usually of large gas capacity and are water cooled, as are the burners themselves, to permit them to withstand the reflected and direct heat that is generated. For more information on equipment for a specific application refer to the chapter covering that application.

CUTTING ATTACHMENTS

As the name implies, a cutting attachment is "a device which is attached to a welding torch to convert it into a cutting torch." When using torches equipped with integral mixing chambers with such an attachment, the mixer should be removed from the torch so that the gases may flow directly into the cutting attachment when it has been screwed into place.

Incidentally, it should be noted that all cutting attachments require that the oxygen valve of the welding torch proper be turned wide open. There is then provided a duplicate valve on the attachment to adjust the proper quantity of preheat oxygen. In addition, the attachment also has a lever to turn on the cutting oxy-

gen. This attachment, and gas cutting in general, is discussed more fully in Chapter 24, on Gas Cutting.

PRESSURE GAS WELDING EQUIPMENT

Pressure gas welding, which is described in Chapter 7, is essentially a mechanized process. Some of the equipment used is conventional for mechanized gas welding and some is special. Basically, the apparatus fulfills three functions: first, to support the parts being welded, keep them in line during welding, and apply pressure; second, to support and oscillate the welding torch; and third, to control the flow and delivery of welding gases.

The degree of simplicity of the equipment depends upon the completeness of mechanization. If the parts to be welded are of simple shape and some manual handling is permissible, the clamping jig can be quite simple. In many cases also, the controls may be relatively simple and the progress of welding may be gaged mostly by visual observation. However, if a higher degree of mechanization is desired or needed to assure best results, the several components of the process can be almost completely mechanized. Special control panels are available for push button control of the entire welding cycle including clamping the pieces, lighting the torch, applying the pressure in the desired sequence, extinguishing the flames, and releasing the pressure and clamps. More detailed descriptions of typical machines are given in Chapter 7.

WELDING RODS AND FLUXES

Welding Rods

Modern oxy-acetylene welding rods vary greatly in chemical composition, according to the composition of the materials to be welded and the strength of welds desired. Rods having a higher carbon content than former low carbon grades and containing higher percentages of silicon and manganese have been developed. Also available are rods alloyed with nickel, chromium, vanadium, molybdenum and other metals. For welding nonferrous metals, alloy rods are used that produce a relatively fine grain weld, free from oxides. A 60% copper and 40% zinc composition modified with manganese and silicon is widely used for welding copper or for braze-welding of steel. Rods are produced in various diameter sizes, ranging from $^{1}/_{16}$ to $^{3}/_{8}$ in. The standard length is 36 inches.

The AWS-ASTM Committee on Filler Metal has prepared the *Tentative Specifications for Iron and Steel Gas-Welding Rods* which are reproduced in Chapter 61. More detailed discussion of welding rods will be found in Chapter 38.

Fluxes

Fluxes for use in oxy-acetylene welding may be obtained in powdered or liquid forms. When using powdered flux, the rod is usually heated and then dipped into the powder, but the powder may also be sprinkled on the base metal if desired. A liquid flux may be painted on the rod and base metal by use of a brush.

The composition of fluxes varies greatly with the base metals and rods with which they are used. For cast-iron welding, a flux consisting of equal parts of carbonate-of-soda and bicarbonate-of-soda may be used. When brazing copper alloys, fluxes containing fused borax and boric acids may be used. Aluminum fluxes may contain portions of alkaline halides. Since chemical characteristics and melting points of metals vary over wide ranges, no one flux can be universally used for all metals.

The essential function of a flux is to combine with, or otherwise render harmless, those products of the welding operation which would interfere with the physical properties of the deposited metal or make the welding operation difficult or impossible.

The oxides of most alloyed metals generally have higher melting points than the metals themselves. These oxides, therefore, remain as solids when the filler metal is in the fluid state. As solids they interfere with metal deposition. Appropriate fluxes will form a fusible slag with the oxides. This slag will tend to flow away from the immediate weld area. The slag will also form a coating over the molten metal, protecting it from atmospheric oxidation.

Fluxes, while in a sense cleaning agents, should never replace proper cleaning of the base metal. They should also be easy to remove upon completion of welding and should cause no corrosive action on the finished weld.

MISCELLANEOUS ACCESSORIES

In addition to the equipment and materials described previously, other accessories are used in the process of gas welding. Only a brief description of such items is included here.

When welding, it is important that the operator be protected from sparks, molten metal and heat radiated from the tip or burner. Suitable gloves and woolen clothing, free from grease and oil, should be worn. When doing heavy work, leather aprons, caps, sleeves and leggings, together with gauntlet type asbestos gloves should be used.

Welders should at all times use goggles or eye shields as a protection against the excessive glare and radiated heat of the flame and molten metal. Also, ample protection is needed to guard against injury from flying sparks or slag chips. Goggles are available with light, medium or dark tinted lenses and durable heat-resistant frames. Reference should be made to Chapter 46 on Safety for additional data on necessary protective clothing.

For actual welding operations, other auxiliary equipment is used. Among the most used of these are the friction lighter, which eliminates the hazard of igniting the gas with a match; the wire brush, for cleaning the work before welding and removing slag after the weld has been completed; and the chipping hammer, for removing slag and peening the weld.

As an economy measure, a *gas saver* can be added to a welding unit. This instrument is fundamentally made up of a hook on which to hang the torch after welding, quick-operating control valves actuated by the torch's weight on the hook, and a pilot for igniting the gas after the removal of the torch from the hook opens the control valves. Where welding is not carried on continuously, this piece of equipment will appreciably lower gas consumption figures.

If for any reason, the volumetric flow rate of the gases used in a welding operation need be known, a rotameter or an orifice meter may be used. The two meters operate basically according to the laws governing flow of gases through orifices. However, a rotameter employs a varying orifice with a constant pressure drop in measuring flow rates, while the orifice meter uses a constant flow area and varying pressure drops.

Other accessories, such as tip cleaners, cylinder trucks, clamps and holding jigs and fixtures, and feeding mechanisms for automatic welding also perform important functions in gas welding.

BIBLIOGRAPHY

Equipment

1. *The Welding Encyclopedia,* Twelfth Edition, The Welding Engineer Publishing Company, 1947.
2. *Oxy-Acetylene Welding and Its Applications,* International Acetylene Association, 1949.

Gases

3. *An Investigation of Maximum Temperatures and Pressures Attainable in the Combustion of Gaseous and Liquid Fuels,* G. A. Goodenough and G. T. Felback, University of Illinois Bulletin, March 17, 1924.
4. *Acetylene and Its Generation,* Associated Factory Mutual Fire Insurance Companies, Bulletin 11.80, 1938.
5. *Acetylene Cylinders, Manifolds and Storage,* Bulletin 11.81, Associated Factory Mutual Fire Insurance Companies, 1938.
6. *Limits of Inflammability of Gases and Vapors,* United States Dept. of the Interior, Bureau of Mines, Bulletin 279, 1939.
7. *Handbook of Chemistry and Physics,* N. A. Lange, Fifth Edition, Handbook Publishers, Inc., 1944.
8. *Handbook Butane-Propane Gases,* Third Edition, Western Business Papers, Inc., 1945.
9. *Safe Practices for Installation and Operation of Oxy-Acetylene Welding and Cutting Equipment,* International Acetylene Association, 1947.
10. *Gas Systems for Welding and Cutting.* Pamphlet No. 51, National Board of Fire Underwriters, 1948.
11. *Theory of the Rotameter,* Fisher and Porter Company.

CHAPTER 5

OXY-ACETYLENE WELDING*

FUNDAMENTALS OF PROCESS

Definition and General Description

OXY-ACETYLENE welding is a gas-welding process wherein coalescence is produced by heating with a gas flame or flames obtained from the combustion of acetylene with oxygen, with or without the application of pressure and with or without the use of filler metal.

The oxygen and acetylene are mixed in the proper proportion in a welding torch (also called a blowpipe) which is designed to give the welder complete control of the welding flame. Oxygen and acetylene are also used as a supply of heat for pressure gas welding. This process is discussed in Chapter 7.

Acetylene is commonly used as the combustible gas in gas welding, because the oxy-acetylene flame, properly adjusted, has an extremely high temperature and because the flame provides a protecting cover over the molten metal during welding. The oxy-acetylene flame produced by burning a mixture of equal volumes of acetylene and oxygen has a higher temperature than any other commercially available gas flame. The high temperature produced by the oxy-acetylene flame is so far above the melting point of most commercial metals that it produces the rapid localized melting necessary for welding. For a discussion of other fuel gases used for gas welding and brazing, see Chapter 6.

Basically, oxy-acetylene welding is the bringing together of two pieces of metal and the melting of the edges in contact by the oxy-acetylene flame produced at the tip of the welding torch. The molten metal from the two edges flows together until they are completely fused, thereby producing one continuous piece of metal when the molten metal has solidified. Filler metal is added in many cases by melting the end of a welding rod into the weld puddle.

The oxy-acetylene flame is also used in the method of welding known as *braze-welding*, wherein the base metal edges are not fused, but joined by the bonding action of the metal deposited from a copper-base welding rod. It differs from brazing itself in that the joint design is the same as would be used for gas welding and capillary attraction is not a factor. The strengths obtained in joining mild steel are comparable to those obtained with gas welding.

The oxy-acetylene flame is also used for preheating in cutting, shaping, and oxygen machining of ferrous metals, and as a convenient source of localized heat for a wide variety of operations, such as flame hardening, flame softening, flame descaling and surfacing. These applications are covered in Chapters 21, 24, and 26, respectively.

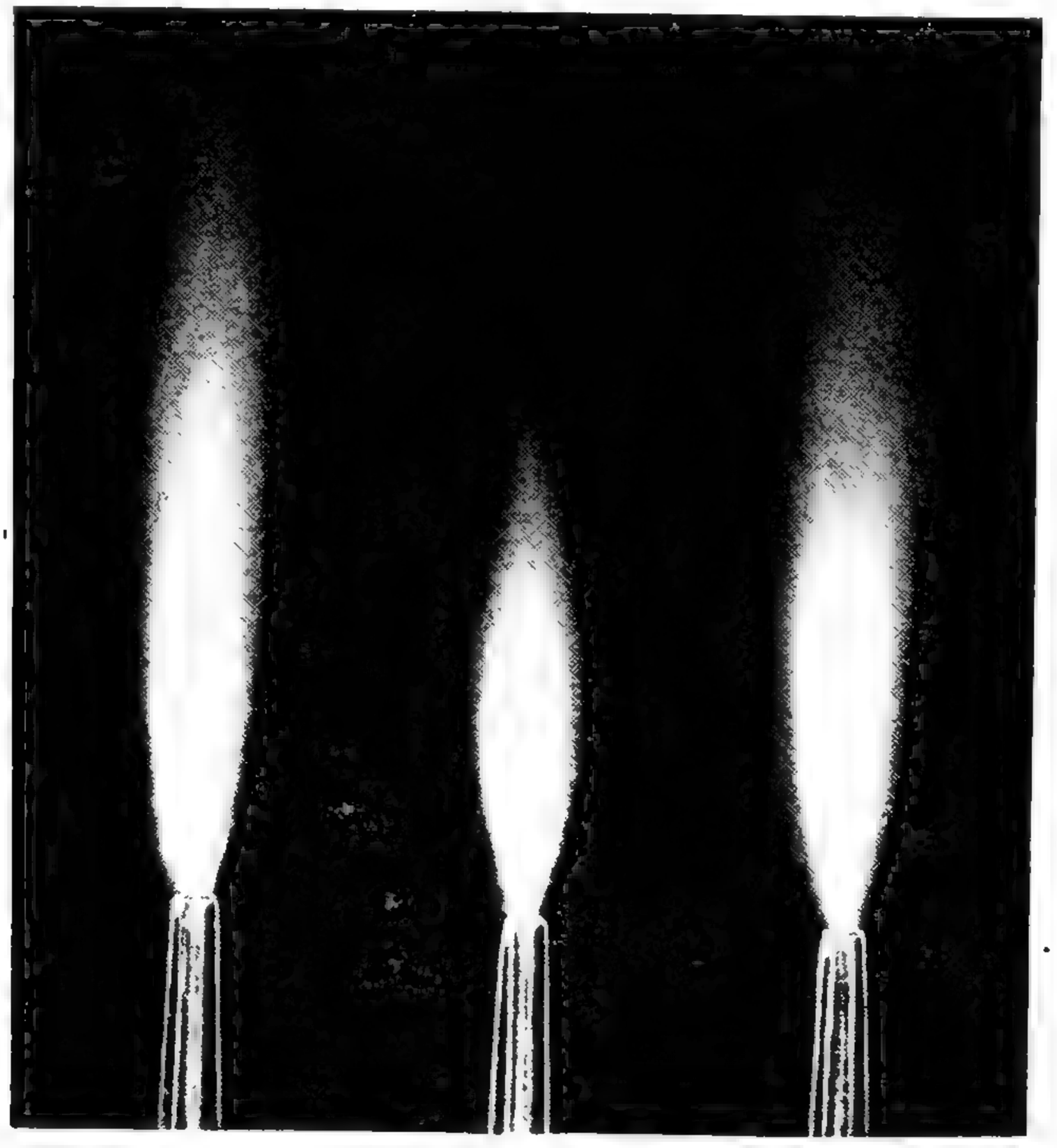
Principles of Operation

Oxy-Acetylene Flame.—The oxy-acetylene torches, tips and regulators are used to form and control the flame, and to apply it at the location desired. By using tips in sizes available, welding flames can be obtained which will vary in diameter from pin size to about $^{3}/_{16}$ inch. The length of the flame will vary with the volume of gases issuing from the tip, the inner cone reaching a length of approximately 1 in. for large flames. The oxy-acetylene flame can be made harsh and violent or soft in action on the surface being heated, by varying gas flow. There are practical limits when welding with the flame as a harsh flame will blow the molten metal from the puddle and a

* Prepared by a committee consisting of J. H. Zimmerman, The Linde Air Products Co., *Chairman*; A. F. Chouinard, National Cylinder Gas Co.; H. V. Inskeep, The Linde Air Products Co.; E. L. Mathy, Victor Equipment Co.; C. A. McClean, Air Reduction Sales Co.; G. W. Plinke, Henry Vogt Machine Co.

flame that is too soft is not stable near the point of application.

The chemical action of the flame on a molten pool of metal can be altered by changing the ratio of volumes of oxygen to acetylene issuing from the tip. Most welding is done with a neutral flame, approximately one-to-one ratio. An oxidizing action can be obtained by increasing the oxygen flow and a carburizing action by increasing the acetylene flow in relation to the oxygen flow. Both these adjustments are valuable aids in welding. For the chemistry of the oxy-acetylene flame, refer to Chapter 4.



Reducing Oxidizing Neutral

Fig. 1.—Flame Adjustments

Flame Adjustment.—Torches should be lighted with a friction lighter. The instructions of the manufacturer of the equipment should govern the procedure of adjusting operating pressures at the regulators and torch valves before igniting the gases issuing from the tip. Three types of flame adjustment are shown in Fig. 1. The neutral flame is easily obtained by making the final adjustment at the torch valves. The start for final adjustment should be made from an excess acetylene flame which is recognized by the *feather* extension of the inner cone. As the flow of acetylene is decreased or the flow of oxygen increased, the feather will disappear. Just at the point of disappearance the neutral flame is obtained.

A practical method of determining the amount of excess acetylene in a flame when a reducing or carburizing flame is desired is to compare the length of the feather with the length of the inner cone measuring both from the torch tip. A 2× excess acetylene flame has an acetylene feather that is double the length of the inner cone. Starting with a neutral flame adjustment, the welder can produce the desired acetylene feather by increasing the acetylene flow (or decreasing the oxygen flow).

The oxidizing flame adjustment is sometimes given as the amount by which the length of the inner cone should be reduced—for example, one-tenth. Starting with the neutral flame the welder can increase the oxygen (or decrease the

acetylene) until the length of the inner cone is decreased the desired amount.

Specifications requiring a reducing flame and mentioning the length of the feather should be adhered to as the carbon pickup in the weld is determined by the excess acetylene in the flame. Where oxidizing flames are necessary, the degree of adjustment is usually determined by the action of the flame on the molten metal. This condition is especially true when welding brass or braze-welding steel.

Technique.—Oxy-acetylene welding may be performed with the torch tip pointed forward in the same direction as the weld progresses. This method is called the *forehand technique* (see Fig. 2*a*). The

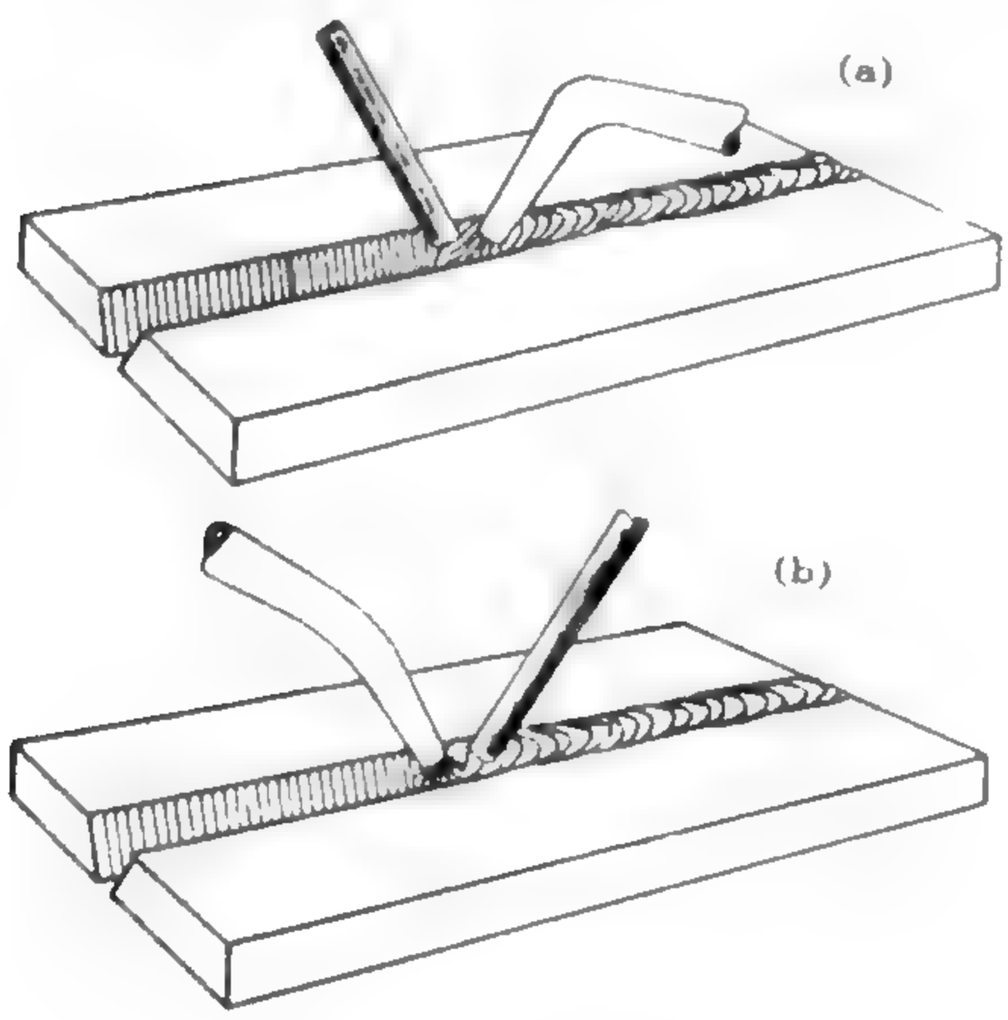


Fig. 2.—(a) Forehand Technique (b) Backhand Technique

tip also can be pointed back toward the metal which has been deposited and this method is called the *backhand technique* (see Fig. 2*b*). Each technique has its advantages, depending on the particular application. In general, the forehand technique is recommended for welding material up to $^1/_8$ in. thick, because of better control of the small weld puddle, resulting in a smoother weld both top and bottom. In these thicknesses the puddle of molten metal is small and easily controlled. A great deal of pipe welding is done using the forehand technique even in wall thicknesses of $^3/_8$ inch.

Increased speeds and better control of the puddle are possible with the backhand technique when welding metal $^1/_8$ in. and thicker. The recommendation that material greater than $^1/_8$ in. in thickness be welded with the backhand technique is based on careful study of the speeds normally achieved with this technique and the greater ease of obtaining fusion at the root of the weld. Backhand welding may be used with a reducing flame when it is desired to melt only the smallest possible amount of steel in making the joint. When the reducing flame is used in welding, the base metal picks up carbon from the flame with the result that this increased carbon content lowers the melting point of a thin layer of steel and results in increased welding speed. Backhand welding using a reducing flame greatly increases the speed of making pipe joints where the wall thickness is $^1/_4$ to $^5/_{16}$ inch. Speeds of three circumferential inches a minute and more are common when using a special multiflame tip and this technique. Backhand welding is sometimes used in surfacing operations.

Base-Metal Preparation.—Cleanliness along the joint and on the sides is of the utmost importance. Dirt and oxides can cause low quality welds and a great deal of trouble for the welder. The defects encountered because of dirt are blowholes, incomplete fusion, slag inclusions and porosity

The necessity for proper spacing between the edges of parts which will be joined dictates some degree of alignment. For a given thickness of material, the root opening should not be so large as to cause difficulty in bridging the gap with molten metal or so small as to prevent full penetration. For production welding, specifications for spacing should be set up and adhered to.

The thickness of the base metal at the joint determines the amount of edge preparation for welding. Thin sheet metal is easily melted completely through by the flame, hence, edges with square faces can be butted together and welded. This type of joint is limited to material about $^3/_{16}$ in. or less in thickness. For thicknesses of $^3/_{16}$ in. to $^1/_4$ in., a slight root opening is necessary for complete penetration but filler metal must be added to compensate for the opening.

Joint edges $^1/_4$ in. and greater in thickness should be beveled. Beveled edges at the joint provide a groove for better penetration and fusion at the sides. The angle of bevel for oxy-acetylene welding varies from 35 to 45 deg., which is equiv-

alent to a variation in the groove angle from 70 to 90 deg., depending on the application. A root face $^1/_{16}$ in. wide is provided but feather edges are sometimes used. Plate thicknesses $^3/_4$ in. and above are double beveled when welding can be done from both sides. The root face can vary from 0 to $^1/_8$ inch. As compared with beveling one side only, beveling both sides reduces the filler metal required approximately one-half and reduces the oxygen and acetylene consumption per foot of weld.

An edge preparation with straight sides is easiest to obtain. This edge can be machined, chipped, ground or oxygen cut. The thin oxide coating on an oxygen-cut surface does not have to be removed as it is not detrimental from the standpoint of the welding operation or the quality of the joint. The bevel angle can be oxygen cut to any desired value. Refer to Chapter 39 for sketches and details.

Braze-Welding.—Braze-welding is an important method of joining metals since less heat is required than in ordinary gas welding because the operation is carried on at a lower temperature. Many metals can be braze-welded. The common example is the braze-welding of cast iron to steel. Steel melts at around 2700° F. and the copper-base filler metal used at around 1650° F. The operation can be performed at temperatures only slightly above the melting point of the filler metal. Braze-welding is used mainly in repair and maintenance work, but many fabricating applications exist.

The main requirement for acceptable results is cleanliness of the joint edges. The surfaces to be joined should be bright and free of oil, dirt and rust. In the presence of a suitable flux and the right amount of heat, the filler metal will flow and tin the joint surfaces. The joint can be completed in one pass or successive passes can be made if the groove is large.

When malleable iron is welded, the melting of the base metal converts the iron to white or hard cast iron. Braze-welding with copper-base filler metal produces a minimum change in the base-metal characteristics and effects a high strength joint.

Using copper-base filler metal on galvanized iron or steel causes a minimum of damage to the coating adjacent to the weld.

Multilayer Welding.—Multilayer welding is used when maximum ductility of a steel weld in the as-welded or stress-relieved condition is desired or if several layers are required to weld thick material. Multilayer welding is accomplished by depositing filler metal in successive passes along the joint until it is filled. Since the *bite* taken with each pass is small, the weld puddle is reduced in size. This procedure enables the welder to devote his attention to securing complete penetration with freedom from icicles and overheating while depositing the first layers. The smaller puddle is more easily controlled and thus the welder can avoid oxides, slag inclusions, cold shuts and incomplete fusion with the base metal.

The increase in ductility in the deposited steel results from the grain refinement in the underlying layers as they are reheated. The final layer will not possess this refinement unless an extra layer is added and removed or the torch is passed over the joint to bring the last deposit up to a normalizing temperature.

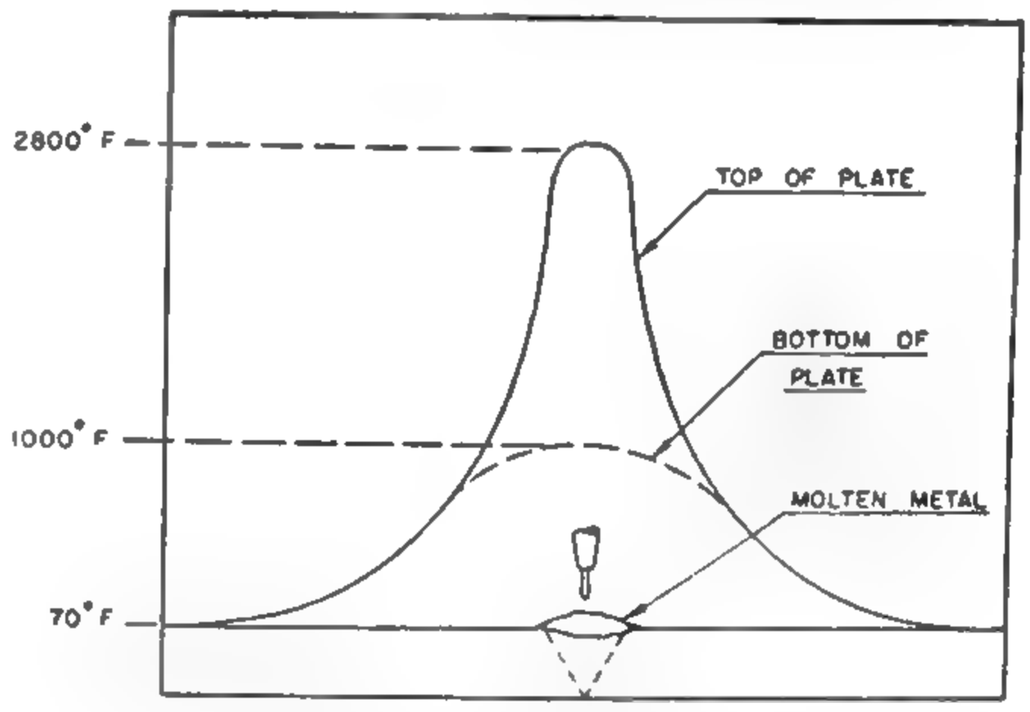


Fig. 3.—Temperature Pattern During Welding
Transverse to Joint, ¼ In. Plate

Effects from Oxy-Acetylene Welding

Distortion.—The steep temperature gradient across the base metal surrounding the joint being welded is a characteristic of oxy-acetylene welding that leads to distortion of the pieces being joined. Various procedures are available to control or reduce this distortion. Figure 3 illustrates representative temperature conditions surrounding the pool of molten metal transverse to the joint line. A somewhat similar pattern exists in a longitudinal direction but the temperature gradients are not symmetrical.

Parts to be welded should be securely tack-welded in place before applying

strength welds, then the section least subject to distortion should be welded first, thus forming a rigid structure for the balance of the assembly.

When design of the structure permits welding from both sides, distortion can be minimized by welding alternately on each side of the joint. Strongbacks or braces can be applied to sections most likely to distort. The welds may be peened to correct distortion. If properly done, this method can overcome severe warpage. A wandering or backstep sequence of welding may be used to control distortion. This method consists primarily of making short welds, with intervening sections left unwelded until the initial welds have partly cooled. Design of a weldment should be such as to minimize distortion during welding.

Metallurgical Effects.—In the area surrounding a weld, the temperature varies from the melting temperature in the weld puddle to ambient temperature in the surrounding metal. In steels, the area near the weld will be heated well above the transformation temperature of the steel, with resulting grain growth and hardening on rapid cooling if sufficient carbon or other hardening element is present. Hardening and grain growth can be minimized in oxy-acetylene welding by playing the flame over the weld and adjacent areas after the weld has been completed. This procedure retards the rapid cooling which normally takes place by conduction through the plate. It is particularly important when the steels being welded are of the so-called air-hardening type. Such steels harden even when relatively slow rates of cooling exist. Hardening of the steel is, of course, to be avoided because of the corresponding loss of ductility or possible cracking in the weld zone.

The oxy-acetylene flame also allows some control of the carbon content of the deposited metal and that portion of the base metal which has been raised to a temperature approaching the liquid state. Use of the oxidizing flame or the presence of mill scale results in a rapid reaction between carbon of the metal and oxygen, with the elimination of the carbon in the form of carbon monoxide. Use of an excess acetylene flame introduces carbon into the weld metal and into adjacent base metal.

Upon being heated to a temperature range between 800 and 1600° F., unstabilized austenitic stainless steel suffers a separation of carbide, which gathers at the grain boundaries and lowers corrosion resistance in the affected areas—those adjoining the weld. If this effect occurs, a further heat treatment after welding is required, unless the steel has been stabilized by the addition of columbium or titanium, and welded with the aid of a columbium-bearing welding rod. The columbium combines with the carbon and minimizes the formation of chromium carbide. All the chromium is left dissolved in the austenitic matrix so that it can resist corrosion to the greatest extent.

Another factor to be considered in welding is the possible tendency to *hot shortness* of the material (a marked loss in strength at high temperatures). If the base metal has this tendency it must be welded with care to prevent hot cracking in the weld zone. Allowances must be made in the welding technique used with these materials and jigging or clamping must be done with caution. Proper welding sequence and multilayer welding with narrow string beads helps to reduce hot cracking. Refer to Chapters 27 to 37 for information on specific materials.

Oxidation and Reduction.—The oxidation of some metals during welding makes it necessary to use fluxes. Manganese and silicon are elements common to plain-carbon steel, and they are important in oxy-acetylene welding because they react readily with oxygen when the metal is molten. The reaction produces a very thin slag cover. This prevents any oxygen contacting the weld metal, and prevents the formation of gas pockets. When the viscosity of this slag covering is properly controlled, the molten metal may be readily kept in position even against the pull of gravity. The action of these elements in oxy-acetylene welding is the same as in steel making. Just as silicon and manganese are used to produce clean, deoxidized metal in open-hearth or electric furnaces these elements are used in the molten weld for the same purpose in oxy-acetylene welding. For this reason, the correct manganese and silicon contents in steel welding rods are important.

The type of flame used in welding various materials plays an important part in securing the most desirable deposit of weld metal. The proper type of flame with the correct welding technique can

be used as a shielding medium which will reduce the oxidizing and nitrogenizing effect of the atmosphere on the molten metal. Such a flame also has the effect of stabilizing the molten weld metal and preventing the burning out of carbon, manganese and other alloying elements.

Weld Quality.—The defects that can occur in welding can be classified into two groups depending on whether they are apparent or not. A visual examination of the underside of a weld will determine whether complete penetration has been obtained, or whether there are excessive globules of metal. Inadequate joint penetration may be due to insufficient chamfering of the edges, too wide a root face, too great a welding speed or poor torch and rod manipulation.

Oversize and undersize welds can be readily observed. Weld gages have been developed that make it easy to determine whether a weld has excessive or insufficient reinforcement. Likewise undercut or overlap at the sides of the welds can usually be seen.

While other defects such as incomplete fusion, porosity, and cracking may or may not be externally apparent, excessive grain growth or the presence of hard spots definitely cannot be determined visually. Incomplete fusion may be a result of insufficient heating of the base metal, too rapid travel or gas or dirt inclusions. Porosity is a result of included gases, usually carbon monoxide, which may be avoided by more careful use of the flame and adequate fluxing where needed. Hard spots and cracking are a result of metallurgical characteristics that were mentioned under metallurgical heat effects.

Inspection.—The term *inspection* usually implies the formal inspection given to welds and welded structures prescribed by a code or the requirements of a purchaser covering the type of construction involved. In so far as welding is concerned the minimum requirements of the codes are inflexible and must be met. Codes vary in their requirements somewhat in respect to the testing and inspection of the finished structure but all have operator qualification procedures. An effort to standardize codes has resulted in uniform conditions where welding is concerned. Chapter 45 contains detailed information on the subject.

The strict code requirements for welder qualifications can sometimes be relaxed where a rough check on a welder's ability is desired. Specimens may be oxygen cut and tested in bending or nick broken in a vise. Welders employed for maintenance and non-critical work can be given a test on this basis cheaply and rapidly. See Chapter 42 for further information on inspection.

EQUIPMENT USED

Chapter 4 describes oxy-acetylene equipment. Torch tip sizes in relation to base metal thickness are given in Chapter 41 and this information can be used as a guide for purchasing or use. The knowledge necessary to weld with the equipment is obtained by training and experience.

Manual Equipment

Any welding torch used by holding in the hand can be classed as manual. Most oxy-acetylene welding is done manually, hence it is important that the equipment be intelligently selected and used. The regulators for any particular size of torch should have capacity enough for the gas flows required. Often oxygen cutting is also done by the welder using either a cutting attachment on a welding torch or a separate cutting torch. Refer to Chapter 24 for cutting information and to Chapter 46 for safety precautions and safe practices in the use and handling of welding and cutting equipment.

Machine Equipment

When high production welding of duplicate parts is needed, automatic or semiautomatic welding machines are used Gas-welded tubing is an example of a practically continuous type of welding operation. Parts like washing machine tubs, sheet steel tanks and containers are welded individually. The gas control system for machine welding requires the use of a sturdier grade of regulator, valve and other equipment than manual welding. Special welding heads or burners are required. Many of these must be of the multiflame type.

Better forming of the components to be machine welded is necessary as compared to manual welding where widely spaced joints can be filled by extra manipulation of the torch and a greater deposition of filler metal. Accurate alignment of groove edges in the jigs or other holding

devices is very necessary. This fact must be kept in mind when designing and building these parts of the welding machine. Whether the machine provides for movement of the material under the torch or movement of the torch over the joint is indicated by the nature of the work. Tube and circumferential welding is best done by moving the work. Longitudinal welds in cylindrical shapes which are relatively short usually are made by moving the torch as the jigs may be heavy and massive. Careful attention must be given to securing the proper distance from the abutting edges of the joint to the edge of the jig or clamp. If this distance is too small, enough heat may be removed from the weld puddle to make welding difficult. If this distance is too great poor alignment is apt to occur when heat buckles the joint area. The correct distance sometimes must be determined by experiment. Where filler metal is needed to make the weld, a rod feed is used. It may be of the gravity type or a force feed by means of rollers contacting the rod.

Welding Rods

Metal deposited during welding should closely match the properties of the base metal. Because of this requirement, welding rods of various chemical compositions have been devised for the welding of many ferrous and nonferrous materials. Obviously, it is important that the correct welding rod be selected for any particular welding problem.

The chemical analysis of good welding rods must be within the limits specified for that particular rod. There are many proprietary rods on the market for which the chemical analysis is not commonly known but which are recommended for specific applications. (See Chapters 38 and 61 for more detailed information.) Filler metal must be free from blowholes, pipes, non-metallic inclusions and any other foreign matter or dirt. The metal should deposit smoothly and not boil or spark excessively. Allowances are made in the chemistry of good welding rods for changes which take place during welding, so that the deposited metal will be of the correct composition. These changes are to be expected, but should occur without undue sparking or spitting and should permit free-flowing metal which will unite readily with the base metal to produce sound, clean welds.

In maintenance and repair work it is not always necessary that the welding rod match the base metal. A steel welding rod of nominal strength can be used to repair parts made of alloy steels broken by overloading or accident. An extreme example of this apparent side-stepping of the rules is the repair of tools such as milling cutters made of high-speed tool steel, using silver alloys as the brazing material. But every effort should be made to match the filler metal and base metal. Where it is necessary to heat treat a steel part after welding, carbon can be added to a deposit of mild steel by the judicious use of the reducing flame, although it is preferable to use a low-alloy steel welding rod.

The welding rod plays a much more complex role than simply supplying the metal to fill the groove. Modern welding rods are the result of extensive research and development. Early filler metal for steel was low-carbon iron and welding rods of this material are still sold for non-critical welding where cost is a factor. But modern rods with their higher tensile strength and greater ductility are used to a far greater extent.

Fluxes

With some metals the reaction of the oxy-acetylene flame and the oxide of the metal are not conducive to easy fusion of the weld metal with the base metal. Usually this condition occurs when the oxides of the metal have a higher melting point than the metal itself. The oxides will not flow from the welding zone but remain to become entrapped in the solidifying metal and interfere with the addition of filler metal. Steel and its oxides and slags which form during welding do not fall in the above category, hence no flux is needed. But aluminum, for example, forms an oxide with a very high melting point and the oxide must be removed from the welding zone before satisfactory results can be obtained. Certain substances have been found which will react chemically with the oxides of most metals forming fusible slags at welding temperature. These substances, either singly or in combination, have been discovered and compounded to make efficient fluxes.

A good flux should have the following characteristics:

1. Assist in removing the oxides oc-

curring during welding by forming fusible slags which will float to the top of the molten puddle and not interfere with the deposition and fusion of filler metal.

2. Protect the molten puddle from atmospheric oxygen and prevent the absorption and reaction of other gases in the flame without obscuring the operator's vision or hampering his manipulation of the molten puddle.

3. Clean and protect the surfaces of the base metal and, in some cases the welding rod, during the preheating and welding periods.

Number 3 above should not be taken to mean that proper cleaning in the preparation of the base metal is not necessary. In fact, additional care in this respect should be taken with base metals and welding rods requiring fluxing.

Fluxes may be prepared as a dry powder, a paste or thick solution, or as a preplaced coating on the welding rod. Some fluxes operate much more favorably if they are used dry. Cast iron and braze-welding fluxes are usually in this class. These fluxes are applied by heating the end of the welding rod and dipping it into the powdered flux. Enough will adhere to flux adequately until the flux-coated portion of the rod is consumed. Dipping the hot rod into the flux recoats another portion. Dropping some of the dry powder on the base metal ahead of the welding zone will sometimes help, especially when repairing dirty and oil-soaked iron castings.

Fluxes in paste form are usually painted on the base metal with a brush and the welding rod can be either painted or dipped. Commercial precoated rods can be used without further preparation but in instances requiring additional flux, it can be placed on the base metal. Sometimes the rod will have to be dipped in powdered flux, if the operator melts the flux off too far from the end.

The common metals and welding rods requiring fluxes are bronze, cast iron, brass, silicon bronzes, stainless steel and aluminum.

COMMON APPLICATIONS

General

Oxy-acetylene welding is used on the whole range of commercial ferrous and nonferrous metals and alloys. As in any welding process, however, physical dimensions and chemical composition must limit the weldability of certain materials and pieces.

In gas welding, the temperature range through which the metal is taken is practically the same as that of the original casting procedure. The base metal in the weld area loses those special properties that were given to it by heat treatment or working. Therefore the ability to weld such materials as high-carbon and high-alloy steels is limited by the equipment available for heat-treating after welding. However, such metals are commonly welded with success, when the size or complicated nature of the piece does not prohibit heat-treating operations.

For wrought iron and plain carbon steels, the welding procedure is straightforward and offers little difficulty to the welder. Sound welds are produced in other materials by appropriate variations in technique, heat-treating, preheating and fluxing.

The oxy-acetylene welding process can be used for welding metal of considerable thickness such as locomotive frames and for the usual assemblies encountered in maintenance and repair. Cast-iron machinery frames a foot or more thick at the fracture point have been repaired by braze-welding.

Iron and Steel

As has been indicated, the low-carbon, low-alloy steels, cast steels and wrought iron are the materials most easily welded by the oxy-acetylene process. Only a simple technique and no fluxes are required.

In oxy-acetylene welding, straight carbon steels having more than 0.35% carbon are considered high-carbon steels, and necessitate special care to maintain their particular properties. Alloy steels of the air-hardening type also require precautions to maintain their properties even though the carbon content may be 0.35% or less. The joint area usually is preheated in order to slow the cooling of the weld caused by conduction of heat into the surrounding base metal. This procedure prevents the hardness and brittleness associated with rapid cooling. If hardening occurs, a postheat treatment is necessary. The welder should use a reducing flame for welding and should

be careful not to overheat the base metal and burn out the carbon. The preheating temperature required depends upon the composition of the steel to be welded. Temperatures of from 300 to 1000° F. have been used.

For stainless and similar steels, several modifications in procedure are required. Because of the high content of chromium or chromium and nickel, these steels have a relatively low heat conductivity. Therefore a smaller flame is recommended than for equal thicknesses of plain carbon steel. A neutral flame is used to minimize oxidation because chromium oxidizes easily. A flux is used to dissolve oxides and protect the weld metal. A high chromium or chromium-nickel steel welding rod supplies the filler metal. Other steels respond well to variations in technique which are discussed in detail in other chapters dealing with these particular problems. (See Chapters 28 to 31.) Table 1 summarizes the basic information for welding ferrous metals.

Cast iron, malleable iron and galvanized iron all present particular problems in welding of any sort. In cast iron, the gray cast-iron structure can be maintained through the weld area by use of preheat, a flux and an appropriate cast-iron welding rod. (See Chapter 27.)

Nonferrous Metals

As is the case with the various ferrous alloys, the particular properties of each nonferrous alloy must be considered in selecting the welding technique used for it. When the logical precautions are taken, little difficulty due to the nature of the metal should be encountered.

For instance, aluminum gives no warning by change in color prior to melting, but appears to collapse suddenly at the melting point. Hence, practice in welding is required to learn to control the rate of fusion. Aluminum and its alloys also suffer from hot-shortness. Therefore, they should be adequately supported at all points heated during the welding. Finally, any exposed aluminum surface is always covered with a layer of oxide which, combining with the flux, forms a fusible slag which floats on the top of the molten metal.

In welding copper, allowances are necessary for chilling of the weld due to the very high thermal conductivity of copper. Preheating is often necessary. Also, considerable distortion can be expected in copper, because the coefficient of thermal expansion is higher than in other commercial metals. These characteristics obviously pose difficulties which must be surmounted in satisfactory welding.

These examples will suggest the type of problems encountered in oxy-acetylene welding, as well as the solutions. In Chapters 27 to 37, concerned with particular metals, the discussion is more detailed.

Table 1—Welding Data—Ferrous Metals

Metal	Flame Adjustment	Flux	Welding Rod
Steel, cast	Neutral	No	Steel
Steel pipe	Neutral	No	Steel
Steel plate	Neutral	No	Steel
Steel sheet	Neutral	No	Steel
	Slightly oxidizing	Yes	Bronze
High-carbon steel	Reducing	No	Steel
Manganese steel	Slightly oxidizing	No	Base metal composition
Cromansil steel	Neutral	No	Steel
Wrought iron	Neutral	No	Steel
Galvanized iron	Neutral	No	Steel
	Slightly oxidizing	Yes	Bronze
Cast iron, gray	Neutral	Yes	Cast iron
	Slightly oxidizing	Yes	Bronze
Cast iron, malleable	Slightly oxidizing	Yes	Bronze
Cast-iron pipe, gray	Neutral	Yes	Cast iron
	Slightly oxidizing	Yes	Bronze
Cast-iron pipe	Neutral	Yes	Cast iron or base metal composition
Chromium nickel	Slightly oxidizing	Yes	Bronze
Chromium-nickel steel castings	Neutral	Yes	Base metal composition 25 12 chromium-nickel steel
Chromium-nickel steel (18-8) and (25-12)	Neutral	Yes	Columbium stainless steel or base metal composition
Chromium steel	Neutral	Yes	Columbium stainless steel or base metal composition
Chromium iron	Neutral	Yes	Columbium stainless steel or base metal composition

Surfacing Operations

Applications of oxy-acetylene welding to surfacing operations are important and common. Since Chapter 21 of this Handbook describes these operations in detail, they merely will be mentioned here.

In surfacing, a layer of metal with the special properties desired is deposited from a welding rod by sweating on or welding to the base metal surface. In this way, a very hard, abrasion-resistant or corrosion-resistant surface may be spread on a mild steel part, and so prolong the part's usefulness. The surfacing operation offers a simple, low-cost means of producing parts that may have two to twenty-five times the life of steel under similar conditions of service. Surfacing materials may be of the work-hardening type or of alloys which are hard in the as-welded condition. Some alloys contain no iron but are made of cobalt, chromium and tungsten. Others are iron-base alloys containing from about 5 to 6% alloy additions. See Chapter 38 for further information on these materials.

Broken edges, gear teeth and mis-machined surfaces can be built up by depositing layers of metal that are like the base metal in composition. The built-up surfaces can then be machined and heat-treated so that they will have the same properties as the original piece. This application makes it possible to reclaim all sorts of damaged pieces and results in savings in part costs and replacement time.

Industrial Applications

The wide field of applications, convenience and economy of oxy-acetylene welding are recognized in practically all of the metal-working industries. The process is widely used in such fabricating industries as: sheet metal, tubing, aircraft, industrial piping and automotive. It is also gainfully used in laying pipe lines and in shipyards as well. See Chapters 47 to 57 for detailed information.

However, the one field in which the process is most widely used and accepted is in maintenance and repair, where its flexibility and mobility result in great savings in time and labor. The typical, small, self-contained unit of an oxygen cylinder and an acetylene cylinder on a two-wheeled stand can be wheeled anywhere in a plant, or easily carried into the field on a small truck, going wherever a breakdown may have occurred. Oxy-acetylene welding has been shown to be particularly suited to the needs of steel mills, railroad shops, machine shops and automobile repair shops, as well as in shops devoted entirely to welding, whose main business may be in repair of many sorts of small and large industrial and household equipment.

The fact that the same gases and equipment can be used in cutting, brazing, soldering, heat treating and surfacing, as well as welding, makes the oxy-acetylene process particularly attractive in so far as convenience and economy in initial investment are concerned.

BIBLIOGRAPHY

1. *Oxy-Acetylene Welding and Its Application,* International Acetylene Association, 1938.
2. *Bronze Welding or Brazing of Iron and Steel by the Oxy-Acetylene Process,* International Acetylene Association, 1938.
3. *Instructions in Oxy-Acetylene Welding and Cutting Processes (Lectures),* Air Reduction Sales Company, 1940.
4. *The Oxy-Acetylene Handbook,* The Linde Air Products Company, 1943.
5. *Stability of Oxy-Acetylene Flames,* L. D. Conta, The Welding Journal, November 1948.
6. *Oxy-Acetylene Welding and Cutting,* S. Plumley, Revised by T. B. Jefferson, McGraw-Hill Book Company, Inc., 1949.

CHAPTER 6

OXY-HYDROGEN, OXY-(OTHER FUEL GAS) AND AIR-ACETYLENE WELDING*

A. OXY-HYDROGEN WELDING

FUNDAMENTALS OF PROCESS

Definition and General Description

OXY-HYDROGEN welding is a gas-welding process wherein coalescence is produced by heating with a gas flame or flames obtained from the combustion of hydrogen with oxygen, without the application of pressure and with or without the use of filler metal.

The formula for the combustion of oxygen and hydrogen in this process is represented by the classical equation for the formation of water vapor from oxygen and hydrogen: $2H_2 + O_2 \rightarrow 2H_2O$. However, visual observation cannot be employed in adjusting an oxy-hydrogen flame to obtain the theoretical proportions of two volumes of hydrogen to one volume of oxygen. The flame is almost invisible, and does not provide any distinguishable index of gas proportions. Therefore it is standard practice in oxy-hydrogen welding to employ torch-supplied, volumetric ratios of hydrogen to oxygen of 2 1/2 to 1, to 6 to 1. (*Torch supplied* is used herein to indicate oxygen supplied from a cylinder or pipe line as distinguished from oxygen derived from the atmosphere.) In practice the operator usually adjusts the oxygen-hydrogen ratio so as to obtain the most heat, but not quite to the point where oxide forms on the weld puddle. Although an increase in the proportion of hydrogen results in a lowering of the flame temperature, this condition does assure a reducing atmosphere in the flame, or what is more important, the absence of an oxidizing condition. Control of the volumetric proportions is secured through adjustment of the hydrogen regulator. Aside from lowering the flame temperature, excess hydrogen will not cause any ill effects since the reducing atmosphere does not leave any carbon deposits.

Oxy-hydrogen welding is a relatively low-flame-temperature operation. Therefore it is used principally for the welding of low-melting-point metals, although there have been limited applications of this process for the welding of steel in light-gage sections and on small parts. The oxy-hydrogen flame is also used to a limited extent for braze-welding and brazing operations where, again, low temperatures are desired. Because of the low temperatures encountered in this process, the heat effects will not be as great as with other welding processes and warping and residual stresses will be less.

Weld Quality

The quality of welds produced with the oxy-hydrogen process is equal to that produced with other processes provided good welding practice is observed. Such weld defects as may be encountered are attributable to the same sources as in other welding processes. About the only peculiar feature of oxy-hydrogen welding is the problem of flame adjustment as discussed above. If an oxidizing flame is used, there will be little visible evidence in the flame to guide the operator. However, the condition will immediately be apparent when the metal is melted because of the formation of oxide.

EQUIPMENT USED

General

Oxy-hydrogen welding is very similar

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in most respects to oxy-acetylene welding and therefore much of the equipment used in the latter process is entirely suitable for oxy-hydrogen welding. Thus the same torches, mixers, tips and hose are used for both. A standard oxygen welding regulator is used on the oxygen cylinder; a regulator specifically designed for use with hydrogen must be employed with the hydrogen cylinder.

In permanent installations where a number of oxy-hydrogen welding operations are carried on simultaneously it is advantageous to manifold both the oxygen and the hydrogen and deliver them to the welding stations through a properly designed and installed piping system.

Virtually no automatic oxy-hydrogen welding is done. There have been mechanized welding and brazing setups developed, but in general these employ standard, manual welding equipment. In automatic brazing operations, using silver alloys, multiflame tips connected to standard torches have been used to a limited extent to provide for mechanized operations on a production basis. These multiflame tips were primarily designed for oxy-acetylene welding and are merely adapted to oxy-hydrogen welding.

It should likewise be noted that for equal heating effects, oxy-hydrogen welding in general will require a larger size tip than would be necessary for oxy-acetylene welding.

Gases

The properties, use, storage and distribution of oxygen are covered in Chapter 4, Gas Welding Equipment. Hydrogen generally is produced by the electrolysis of water. It is shipped, at a pressure of about 1800 psi., in steel cylinders having capacities of about 176 cu. ft. or 2000 psi. and 194 cu. ft. according to regulations of the Interstate Commerce Commission. The hydrogen in these cylinders is of a purity of about 99.5%. The conventional hydrogen cylinder is similar in appearance to an oxygen cylinder but is distinguishable by distinctive color marking and has different cylinder valve threads.

The procedure for and the safety regulations applying to the connecting of an oxy-hydrogen welding outfit are similar to those detailed for oxy-acetylene equipment. (See Chapters 4 and 46.) The fact that hydrogen is a colorless, odorless and tasteless gas must be recognized and care must be exercised to prevent its escape in unventilated spaces.

COMMON APPLICATIONS

The oxy-hydrogen flame supplies a source of heat for such low-temperature operations as the welding of low-melting-point metals, brazing and braze-welding. The versatility of the oxy-acetylene flame enables it to perform a wide variety of welding operations, but the feature of high flame temperature coupled with high heat capacity may at times prove undesirable.

The oxy-hydrogen flame finds extensive use in the welding of aluminum and its alloys, particularly in the thinner sections. Here the lower flame temperature and heat input make control of the molten metal easier than with the oxy-acetylene flame. Joint designs, welding techniques, and the use of filler metal and flux are the same with oxy-hydrogen welding as with oxy-acetylene welding which is covered in Chapter 5. (See Chapter 32 for further information on the welding of aluminum.)

The welding of lead (often erroneously referred to as *lead burning*) is another field for the oxy-hydrogen flame. The low-melting point of this metal dictates the use of this flame. Oxy-hydrogen welding is preferred for lead in thicknesses up to about $^1/_4$ or $^3/_8$ inch. For greater thicknesses the oxy-acetylene flame is generally used because of the greater heat required. Another advantage in the use of oxy-hydrogen welding for lead is the fact that it will not yield deposits of carbon which accelerate corrosion in welded lead assemblies. (See Chapter 36 for further information on the welding of lead.)

Magnesium and its alloys represent another field for oxy-hydrogen welding. The welding of magnesium is similar in many respects to the welding of aluminum. (See Chapter 33 for further information on the welding of magnesium.)

The oxy-hydrogen flame finds limited use in torch brazing, using silver brazing alloys. In such applications the operations are usually mechanized, the oxy-hydrogen flame affording a means of controlling the extent of heating. Usually the heat is applied through flat tips, each equipped with a multiplicity of

small, closely spaced orifices. The parts to be brazed, after being cleaned, fluxed and having the alloy preplaced, are mechanically fed through the zone of the heating flames.

B. OXY-(OTHER FUEL GAS) WELDING

FUNDAMENTALS OF PROCESS

Definition and General Description

There are many fuel gases which may be burned with oxygen as a source of heat. Some of these are obtained as by-products of other processes, some are manufactured and others are obtained from nature. In general, the flame temperatures resulting from combustion of these fuel gases when burned with oxygen are lower than those obtainable with oxy-acetylene or oxy-hydrogen flames. However, under some conditions these lower flame temperatures may be desirable. In addition, their economic availability may dictate their use in special conditions. Among these other fuel gases more commonly used in welding and brazing operations are:

1. *Manufactured gas:* a mixture of carburetted water gas and/or coal gas enriched with gas oils or natural gas. (Sometimes called *city gas.*)
2. *Natural gas:* obtained from natural gas wells. Its principal constituent is methane, although its specific composition varies with locality.
3. *Propane, Butane:* These and other hydrocarbon gases are largely petroleum derivatives.

Weld Quality

Where used, these processes produce welds of quality equal to that obtained with other welding processes. Where propane or butane is used, the problem of securing a non-oxidizing flame of sufficient temperature limits the field of application.

EQUIPMENT USED

General

Except for fuel-gas regulators the equipment used, including torches, tips and hose, is the same as that used for oxy-acetylene or oxy-hydrogen welding. However, since the welding operations are lighter, the smaller sizes of equipment are used. In addition, cupped or skirted tips are sometimes used for brazing.

It is possible to manifold these fuel gases, in a manner similar to that employed for other fuel gases, where the magnitude of operation warrants. (This is a fairly common practice where these fuel gases are used for cutting.)

Gases

The properties of these fuel gases are covered in Chapter 4.

Manufactured and natural gases are generally taken from the gas mains. Propane, butane, etc., are stored and shipped in pressure containers subject to the regulations of the ICC. The usual safety precautions should be observed when handling these gases.

COMMON APPLICATIONS

The most common applications for oxy-(other fuel gas) welding are the welding of lead, and torch brazing using silver brazing alloys.

C. AIR-ACETYLENE WELDING

FUNDAMENTALS OF PROCESS

Definition and General Description

Air-acetylene welding is a gas-welding process wherein coalescence is produced by heating with a gas flame or flames obtained from the combustion of acetylene with air, without the application of pressure and with or without the use of filler metal.

When a fuel gas is burned with air the flame temperature is lower than that obtained with the same gas burned with oxygen. The reason for this is apparent when it is remembered that air contains approximately $^4/_5$ by volume of nitrogen which is neither a fuel gas nor supporter of combustion. Therefore acetylene burned with air produces even lower flame temperatures than the gas combinations discussed in sections A and B of this Chapter. The heat available also is lowered; therefore the air-acetylene flame is suitable only for welding light sections of lead, light brazing operations and soft-soldering.

Within this limited field of application, the quality of welds is satisfactory.

EQUIPMENT USED

Torches for air-acetylene welding are generally designed to operate on the Bunsen burner principle, i.e., the acetylene flowing under pressure aspirates the appropriate amount of air to provide combustion. For small operations, the acetylene usually is supplied from a small cylinder which is frequently equipped with a pressure-reducing valve. For somewhat larger operations, and those small cylinders not equipped with pressure reducing valves, an acetylene pressure reducing regulator is necessary. Since a hose is not required for the air, only one hose is needed—to convey the acetylene to the torch. Flame adjustment is obtained by adjusting the amount of air admitted to the Bunsen jet.

COMMON APPLICATIONS

Air-acetylene welding is sometimes used for welding lead up to about $^{3}/_{16}$ or $^{1}/_{4}$ inch. Another field of application is torch brazing with silver brazing alloys where the mass of parts is such that the limited heat required can be supplied by this type of equipment. Perhaps the greatest field of application for air-acetylene equipment is in soft-soldering copper pipe joints and electrical connections.

BIBLIOGRAPHY

1. *Welding Aluminum and Its Alloys by Arc, Torch and Pressure Processes,* W. Spraragen and G. E. Claussen, The Welding Journal Res. Suppl., January 1941.
2. *Lead Welding,* W. Spraragen and G. E. Claussen, The Welding Journal Res. Suppl., February 1941.
3. *Aluminum Welding with Liquefied Gas,* J. V. Kielb, The Iron Age, May 4, 1944.
4. *Joining Aluminum Alloys,* E. C. Hartman and G. O. Hoglund, Steel, August 14, 1944.
5. *Present-Day Brazing Production Possibilities,* A. N. Kugler, Machinery, May 1945.
6. *Brazing for Strength with Economy,* L. D. Jennings, Aero Digest, November 1, 1945.
7. Transactions of the Am. Soc. of Mechanical Engineers, 1945.
8. *How to Weld Aluminum,* Reynolds Metals, Inc., The Iron Age, June 20, 1946.
9. *Lead Welding,* R. L. Ziegfeld and D. M. Borcina, Steel, August 5, 1946.
10. *Brazing and Allied Process, Part I—Introduction, Supplies, Equipment and Applications,* R. S. Lindenmeyer, Science and Mechanics, August 1947.
11. *Brazing and Allied Process, Part III—Silver Alloy and Aluminum Brazing Techniques,* R. S. Lindemeyer, Science and Mechanics, December 1947.
12. *How Brazing Methods Affect Design Details,* S. DeDomenico and A. Squire, Product Engineering, April 1948.
13. *Welding of Aluminum and Aluminum Alloys with Reference to Manufacture of Pressure Vessels,* Report No. PB34016, Office of Technical Services, Dept. of Commerce.

CHAPTER 7

PRESSURE GAS WELDING*

FUNDAMENTALS OF PROCESS

Definition and General Description

PRESSURE GAS welding is a gas-welding process wherein coalescence is produced simultaneously over the entire area of abutting surfaces, by heating with gas flames obtained from the combustion of acetylene with oxygen and by the application of pressure without the use of filler metal. The two modifications in use are the closed-joint and the open-joint methods. In the closed-joint method, the clean square faces of the parts to be joined are butted together under moderate pressure and heated by gas flames until a predetermined upsetting of the joint occurs. In the open-joint method, the faces to be joined are individually heated by the gas flames to the melting temperature and then brought into contact for upsetting. The process in both modifications is ideally adapted to mechanized operation, and practically all commercial applications are either partially or fully mechanized. Pressure gas welding is being used for welding the complete range of low- and high-carbon, low- and high-alloy steels, and several of the nonferrous metals and alloys, but at the present time is applicable only to the making of butt joints.

As the metal along the interface in the closed-joint method does not attain the melting point, the mode of welding is different from that in fusion-type welding. Generally speaking, welding takes place by the action of grain growth, diffusion and grain coalescence across the interface under the impetus of high temperature—about 2200° F. for low-carbon steel—and upsetting or pressure. That these forces are capable of creating a high-grade weld has been amply demonstrated in several research programs. The welds thus made are characterized by a smooth-surfaced bulge or upset at the weld (see Fig. 1), and the general absence of fused metal in the weld zone. In the open-joint method, welding takes place in the molten state, but most of the melted metal is squeezed from the interface by impact pressure. The welds thus made resemble flash welds in general appearance.

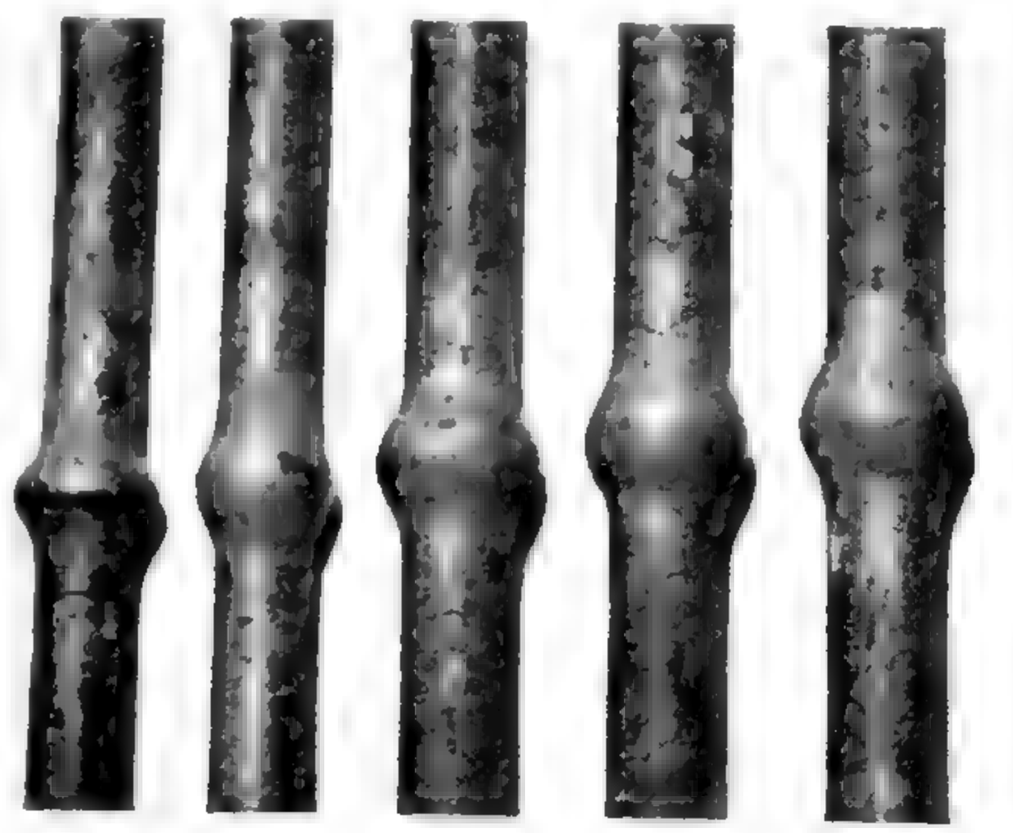

Fig. 1.—Typical Pressure Welds in 1- and 1¼-In. Diam. Bars

Principles of Operation

Closed-Joint Method

The faces to be welded are butted together, and an initial end pressure is applied prior to the start of the welding cycle to assure intimate contact of weld faces. The metal is heated and, after proper temperature has been reached, is upset sufficiently to produce a weld.

Torches.—Heating is generally done by means of multiflame oxy-acetylene torches of the water-cooled type. These are designed to generate sufficient heat and to distribute this heat uniformly through-

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out all sections to be welded. Simple sections, such as squares or rectangles, may be heated from two or four sides with flat-faced heating heads. For sections over 1 in. in thickness, it is advisable to heat from all sides, as shown in Fig. 2. It is often necessary to take precautions against overheating of corners when heating square-ended specimens from all sides by using smaller-sized flame ports at the ends of the torches.

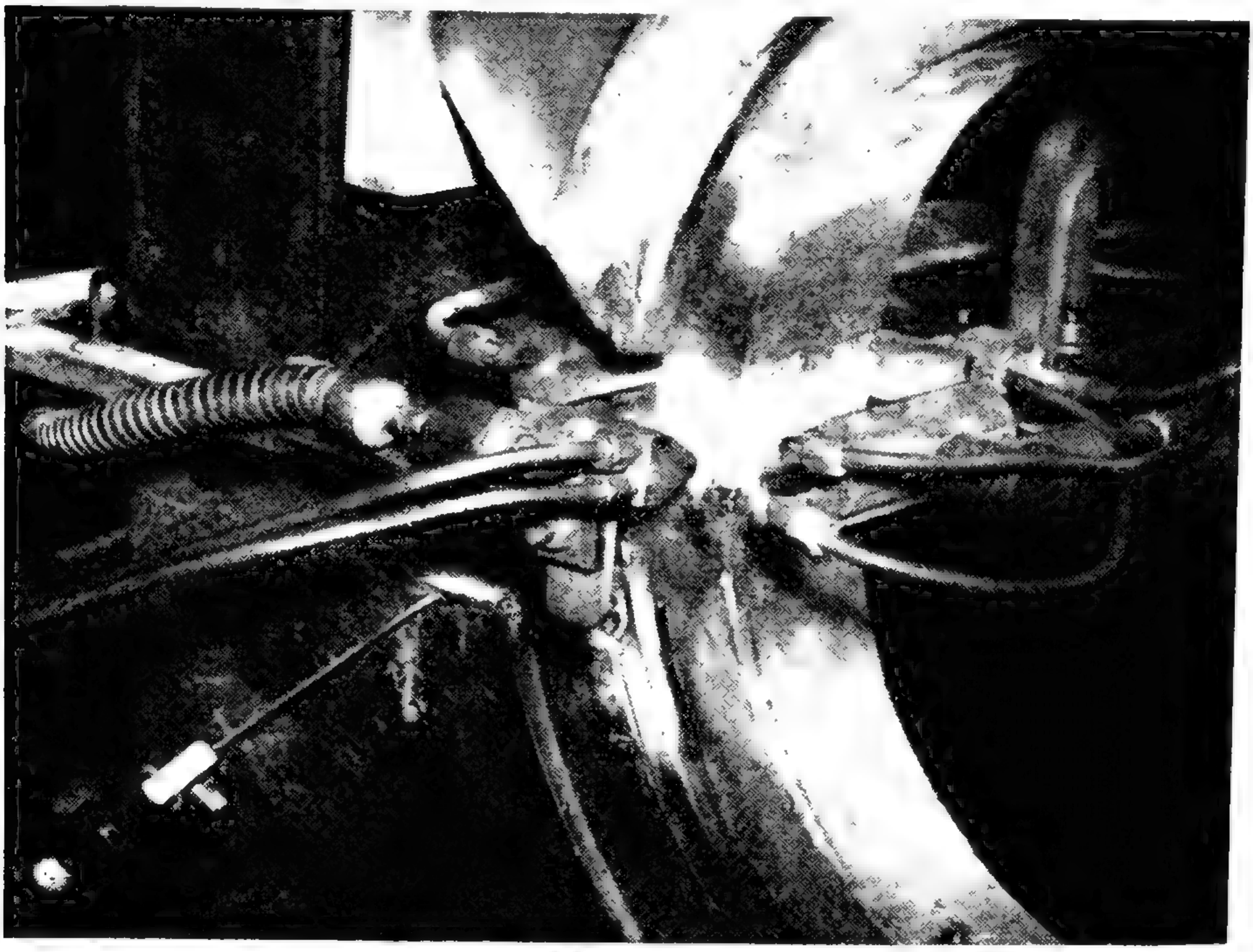

Fig. 2.—Torch Arrangement Used for Welding a Ring of Type 321 Stainless Steel in a $1^{7}/_{8}$- by $2^{5}/_{8}$-In. Section

This is particularly true of the high-carbon steels and such alloys as unstabilized stainless steels. Except for welding material less than $^{1}/_{4}$-in. thick, the torches are usually oscillated across the interface through a path about equal in length to the thickness of the material. This prevents local overheating and promotes penetration of the heat into the full section being welded.

Solid or hollow rounds, such as shafts or piping, are usually welded with circular ring burners which may be of the split type for easy loading and removal of work from the welding machine. A typical head of this type is shown in Fig. 3, for welding $2^{1}/_{2}$-in. diam. by $^{1}/_{4}$-in. wall tubing.

When more complicated shapes are to be welded, more elaborate heating heads are required. These should conform to the shape to be welded in such a manner that uniform heating will result throughout the section to be welded. Examples of such heads are those used for welding railroad rails and also those used for welding two forgings to form an aircraft propeller barrel assembly as shown in Fig. 4.

In general practice, each heating head is supplied with mixed gases from a separate mixer or torch connected through a separate set of oxygen and acetylene regulators to the main gas supply. In this manner, the gas flow, hence heat delivery, of each head can be adjusted individually and maintained within close limits. The best practice in this respect requires that the oxygen needle

Fig. 3.—Split Annular Torch for Pressure-Welding Piping, Tubing or Solid Rounds

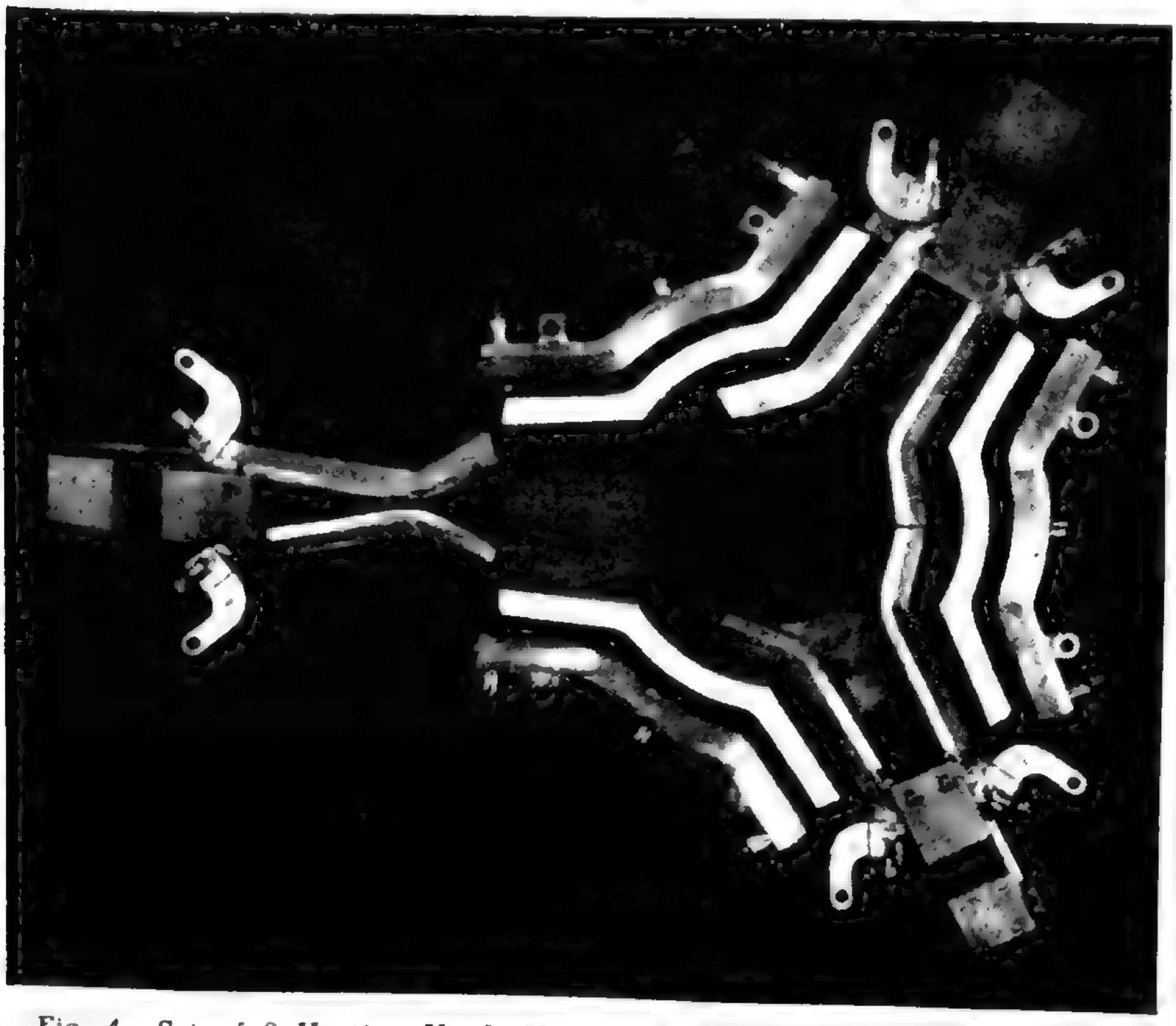

Fig. 4.—Set of 9 Heating Heads Used for Welding Aircraft Propeller Barrel Assemblies. The Part Being Welded Is Shown in the White-Colored Sections. The Pair of Heads on the Left Is Shown in the Retracted Position

valve on the torch be wide open, and that all regulation of oxygen flow be accomplished at the regulator. The acetylene should be adjusted to a faint feather to assure the absence of an oxidizing flame. Where a volume of less than 250 cu. ft. per hr. is required for each head, ordinary manual welding torches may be used with proper adapters for connecting to the heating heads, but with greater flows, larger machine-type torches will be necessary. In special applications requiring the use of multiple heating heads, and when it is important that the heat delivery by all heads be closely similar, they may be manifolded in such a manner that equal amounts of gases are automatically delivered to each head. It is preferable in all cases that the torch or mixer be placed relatively close to the heating head but far enough away from the hot gases to avoid trouble from overheating.

ing. Adequate provision for maintaining parallelism of pressure application is therefore essential.

End Preparation.—The quality and type of end preparation of surfaces to be welded are dependent upon the type of steel. In general, good-quality welds are made most easily and consistently if the abutting ends are machined or ground to a smooth, clean surface. Freedom from oil, rust, grinding dust and other foreign material is of greatest importance, and cleaning of the surfaces with a suitable solvent is general practice. The geometry of the abutting faces depends upon the application and material used. For welding low-carbon steels, the abutting faces are usually beveled to a 6- to 10-deg. included angle, the open side of the angle facing the flames. With higher carbon steel and the low-alloy and high-alloy steels, the abutting faces should be square,

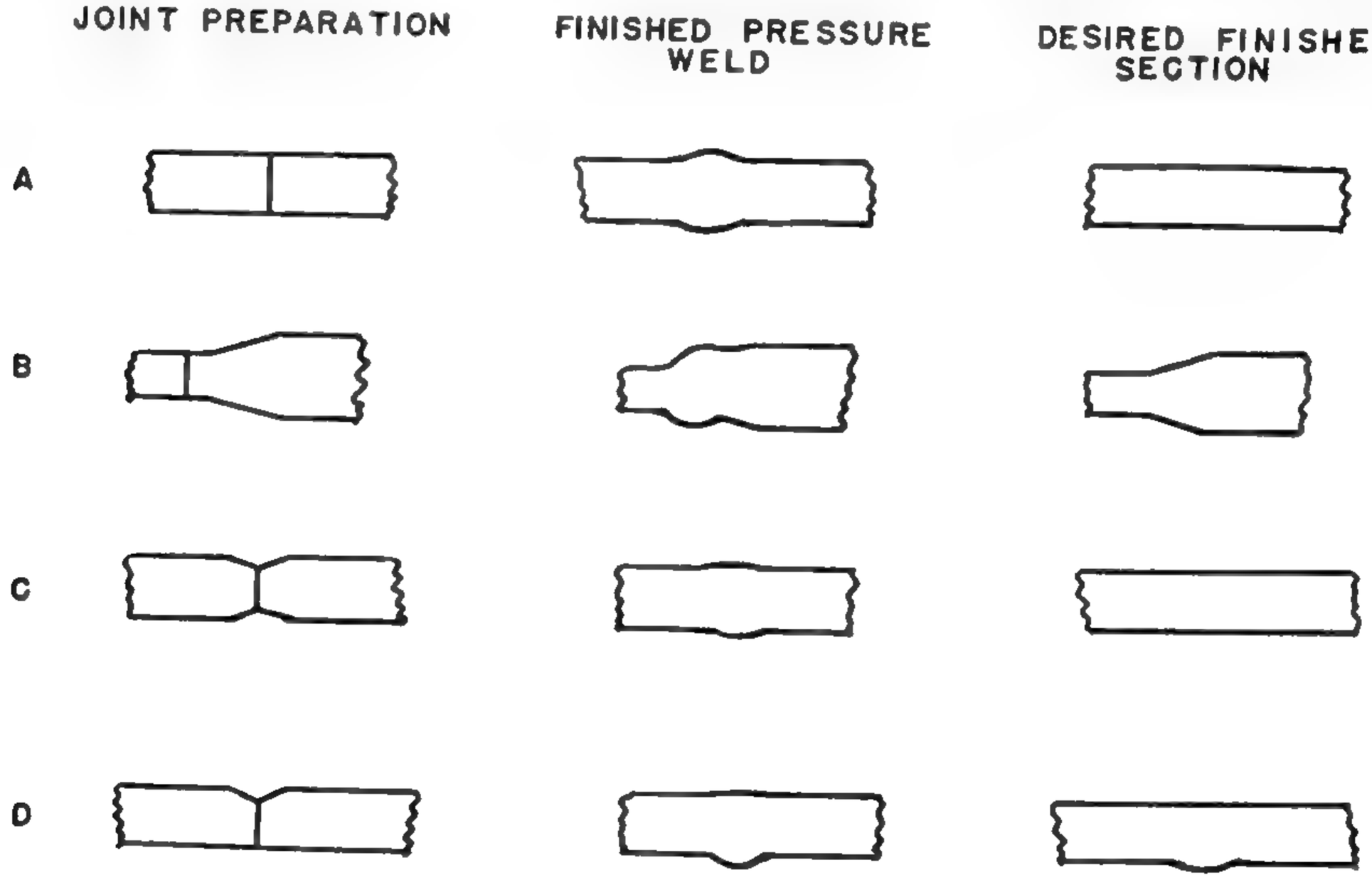

Fig. 5.—Joint Designs for Pressure Gas Welding

Pressure and Alignment Requirements.—The apparatus for pressure-welding must be designed not only to apply the desired pressure, but also to prevent side-slipping and misalignment while the assembly is in the plastic state during welding. Adequate provision for maintaining parallelism of pressure application is therefore essential.

End Preparation.—The quality and type of end preparation of surfaces to be welded are dependent upon the type of steel. In general, good-quality welds are made most easily and consistently if the abutting ends are machined or ground to a smooth, clean surface. Freedom from oil, rust, grinding dust and other foreign material is of greatest importance, and cleaning of the surfaces with a suitable solvent is general practice. The geometry of the abutting faces depends upon the application and material used. For welding low-carbon steels, the abutting faces are usually beveled to a 6- to 10-deg. included angle, the open side of the angle facing the flames. With higher carbon steel and the low-alloy and high-alloy steels, the abutting faces should be square, flat and smooth. This also holds for such nonferrous alloys as Monel, Nichrome and copper. Some control of the shape of the upset can be obtained by pre-beveling of the parts or by proper disposition of the weld zone. Figure 5 illustrates

typical joint preparations for pressure gas welding and the disposition of the metal in the completed weld.

Welding Cycle.—The general procedure for setting up a pressure gas welding operation is as follows: Assume that it is desired to weld two 5-in. diam. by $^1/_4$-in. wall steel pipes. For welding material of this thickness, heat may be applied from one side only and for convenience is usually applied from the outside. A split head is therefore obtained which will provide small oxy-acetylene flames at intervals of about $^1/_4$ in. for the full circumference of the pipe. The head is usually made so that the tips of the flames are about $^3/_8$ in. from the original face of the pipe. The required gas flow may be judged from the curve in Fig. 6 showing gas consumption per foot per inch of thickness. Usually the flame

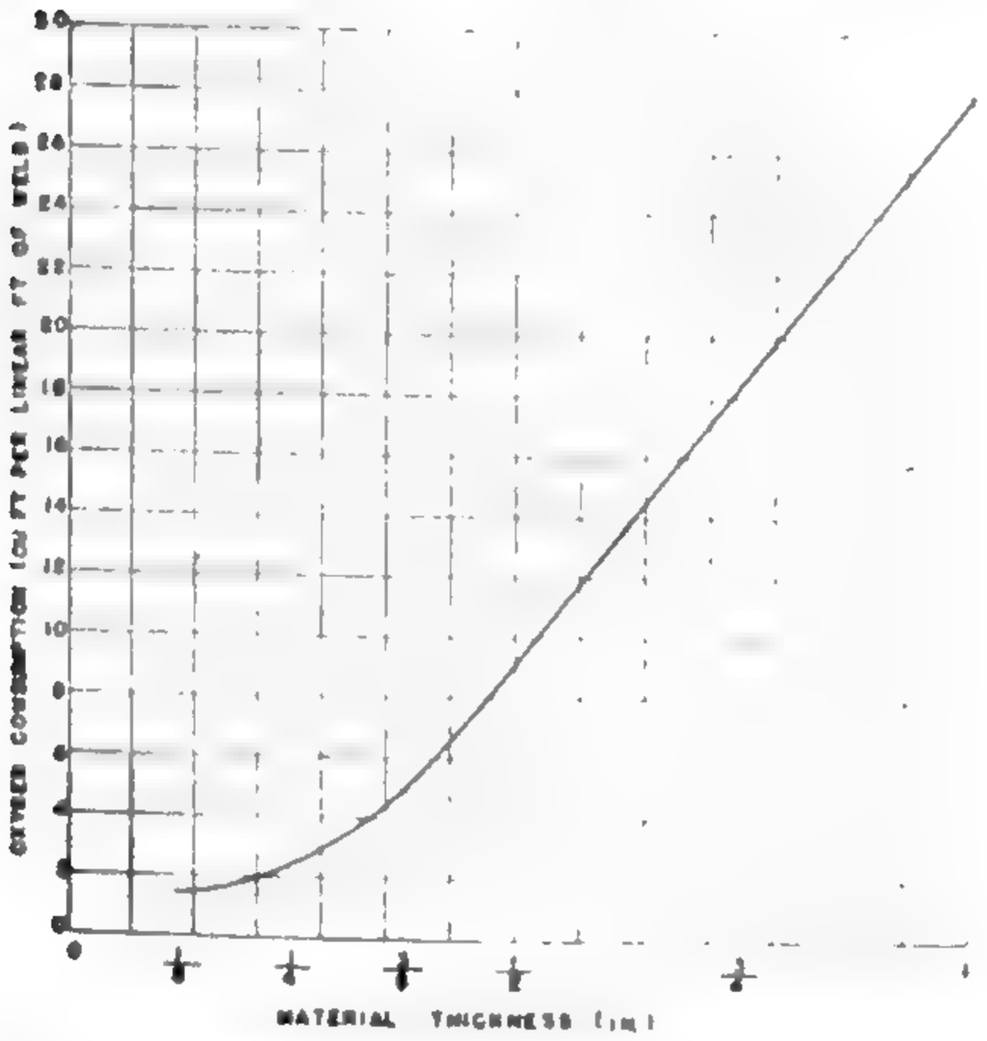

Fig. 6.—Oxygen Consumption vs. Material Thickness

creasing temperature, the steel becomes unable to support the initial load. The time at which this occurs should be close to that indicated on Fig. 7, or about one minute for $^1/_4$-in. material. At this time the metal is at welding temperature for its full thickness, and the upsetting pressure equal to 4000 psi. or 15,600 lb. total pressure is applied until the weld zone shortens $^3/_{16}$ in., which is the preferred shortening for steel of this thickness.

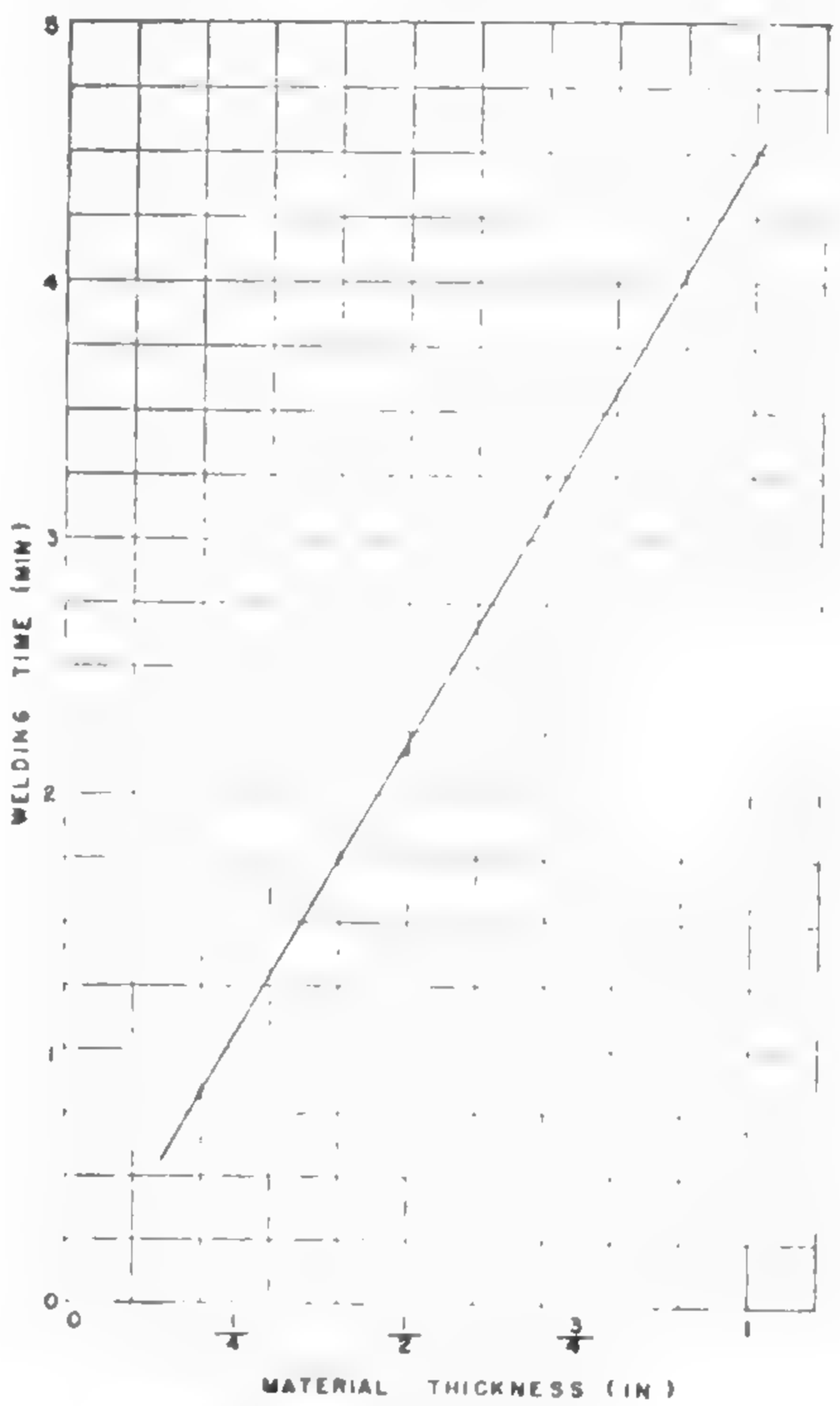

Fig. 7.—Welding Time vs. Material Thickness

The torches may then be extinguished and the assembly removed from the machine.

There are a few modifications of this basic method, the principal variation being in the sequence of application of pressure. These modifications are introduced to conform to the special requirements of some metals. For instance, the constant pressure method is recommended for welding high-carbon steels, such as rails and reinforcing bars. The predetermined welding pressure, for instance 2800 psi. for rail steel, is applied when the work is lined up in the machine and is

ports are about No. 73 drill size. The head is mounted in the same plane as the interface with provision for some oscillation. The abutting ends of the pipe are beveled to an included angle of 6 to 10 degrees with a smooth, clean finish. The pipes are placed in the machine, lined up and an end pressure equal to 1500 psi.—or in this case 5850 lb. total pressure—is applied. While this pressure is maintained, the heads are lighted and oscillated through a short stroke across the weld joint. As the weld zone heats up, the beveled ends close, preventing any oxidation at high temperature. With in-

maintained continuously during the entire cycle. The metal starts to upset gradually at a temperature considerably below the melting point of the metal, and heating and upsetting are continued until a predetermined shortening of the weld zone has taken place. With this method, the welding conditions and amount of upset are selected to allow pieces to attain the proper temperature, usually between 2000 and 2200° F., before the end of the welding period. The heating torches are turned off, either manually or automatically, after the upsetting has been halted. The pressure may be immediately released or retained until after the metal has cooled somewhat in order to avoid possible distortion in handling.

A second variation of the basic method is especially applicable to high-chromium steels and nonferrous metals. A high initial pressure of 6000 to 10,000 psi. is applied before the heating is started and is maintained only until the metal in the weld zone starts upsetting. This pressure keeps the faces in close abutment and prevents oxidation of the interfaces. The pressure is then reduced until the metal has attained the necessary temperature, at which time the pressure is again raised to produce a rapid upsetting action. The low intermediate pressure may be adjusted so that the metal just begins to upset as proper temperature is attained, and thereby serves as an indirect guide to ensure proper temperature. The high initial pressure may also be adjusted to allow upsetting to take place at a maximum temperature of 1400° F., and thereby seal the faces before they have a chance to oxidize. This method has also been found useful for welding pipe lines when the occasional out-of-round or out-of-square ends are encountered. Where this condition exists, good welds can be produced by applying a pressure of about 4000 psi. to the ends and keeping the torch stationary over the joint, thus closing the abutting surfaces without oxidation of the interface. After this preliminary step, welding continues in accordance with the established procedure.

Examples of typical pressure cycles used in pressure gas welding are given in Table 1. Table 2 gives data on the average dimensions of closed-joint pressure welds in material of various thicknesses.

Table 1—Typical Pressure Cycles

Type of Metal	Method	End Pressure, Psi.		
		Initial	Intermediate	Final
Low-carbon steel	Closed joint	500–1500	....	4,000
High-carbon steel	Closed joint	2,700	....	2,700
Stainless steel	Closed joint	10,000	5,000	10,000
Monel	Closed joint	6,500	....	6,500
Steel, carbon and alloy	Open joint	....	....	4000–5000

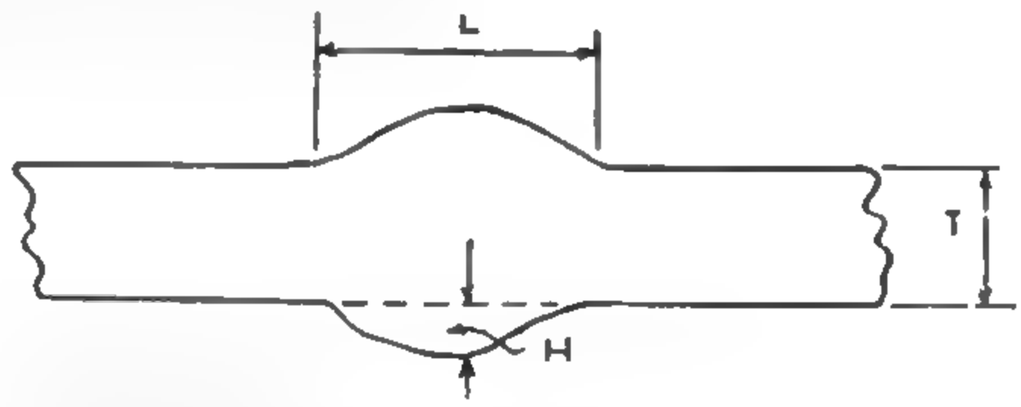

Table 2—Joint Dimension Data for Pressure Welds[a] with Plain Butt Joints, Closed-Joint Method

Material Thickness or Diameter, In., *T*	Length of Upset In., *L*	Approximate Height of Upset, In., *H*	Total Shortening, In.
1/8	3/16–1/4	1/16	1/8
1/4	5/16–1/2	3/32	1/4
3/8	9/16–5/8	1/8	5/16
1/2	3/4–7/8	3/16	3/8
3/4	1 1/16–1 3/16	1/4	1/2
1	1 1/4–1 1/2	3/8	5/8

[a] These hold only for applications where heat is applied to both faces. For open-joint method the dimensions are usually unspecified as they depend upon the welding conditions.

Upsetting.—The quality of the weld depends to an important degree upon the attainment of proper shortening during the welding operation. The amount of shortening or longitudinal contraction of the weld zone is proportional to the

thickness of the material. Recommended amounts of shortening are given in Table 2. These values are usually measured from fixed points either on the specimens or on the clamping jigs.

Open-Joint Method

Torches.—The most satisfactory heating head is a flat multiflame-type burner such as shown in Fig. 8 which gives a uniform flame pattern conforming to the cross-section of the members to be welded.

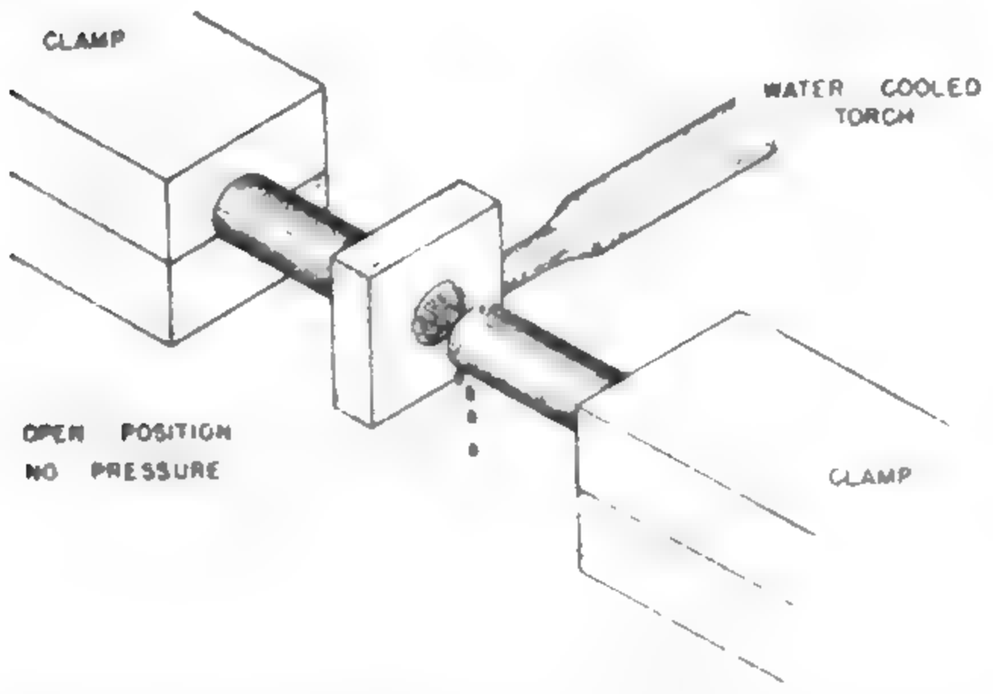

Fig. 8.—Schematic Drawing of Torch and General Setup for the Open-Joint Method of Pressure Gas Welding

An alternative type of head, providing a single or double line of flames directed into the opening of the joint, represents a satisfactory type that can be used successfully for welding thin sheet material. Both types of heating heads are water-cooled.

Good alignment of the heating head with respect to the faces of the joint is important to avoid oxygen absorption and to obtain uniform melting and subsequent upsetting. A removable spacer block accomplishes this function rapidly and accurately.

Actual gas flows will vary with the size and shape of the pieces to be welded. With bars of small diameter, flows as high as 250 cu. ft. per hr. of acetylene per square inch of cross-section are often used, and the faces are brought to a molten condition in a few seconds. On large sections, practical design considerations may reduce the gas consumption to as low as 60 cu. ft. per hr. of acetylene per square inch of cross-section with a corresponding increase in heating time.

Pressure and Alignment Requirements.—Machines for open-joint pressure gas welding must provide more accurate alignment and must be of more rugged construction than machines for the closed-joint method in order to absorb the impact forces resulting from the rapid, almost impact, closure. Machines similar to those used for flash welding are quite suitable.

End Preparation.—Since the ends are thoroughly melted before the weld is made, a saw cut is as satisfactory as a finely ground surface. A thin layer of rust has little effect on the quality of the subsequent weld, but major amounts of foreign substances such as rust or oil should be removed before welding.

Welding Cycle.—The general procedure for open-joint pressure gas welding is to align the specimens with the suitable torch placed between the opposing ends or, in the case of thin materials, so that the flames pass between the opposing ends for the full length of the seam. The torches are lighted and the flames are directed against the ends of the specimens until a film of molten metal develops over the entire surface. The torch is then rapidly withdrawn, and the faces are brought together as rapidly as possible with a constant pressure of 4000 to 5000 psi. No heating is applied during the upsetting, and the pressure is maintained until the upsetting ceases. Care is taken not to release the grips before the weld zone is properly solidified in order to avoid warping. Figure 9 shows the typical appearance of a pressure weld made in this manner.

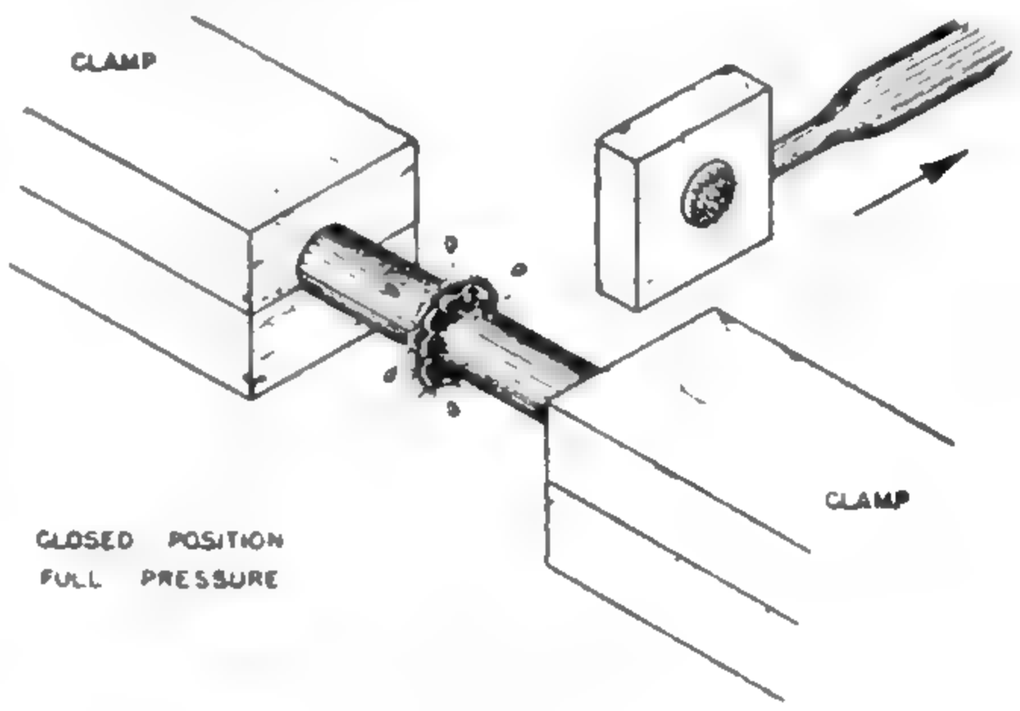

Fig. 9.—Schematic Drawing of Open-Joint Pressure Weld at Time of Impact

Upsetting.—The total upset is controlled by the pressure used and by the resistance of the hot, plastic metal. Therefore, no fixed amount of upsetting or shortening is required.

Effect of Process on Metals Welded

In general, pressure gas welding has a minimum effect on the mechanical and other properties of the base metals involved. Owing to the high heat content of the metal in the weld zone, the cooling rate following pressure gas welding is quite low. Tests have shown that on base metal over 1-in. thick, it approximates the rate at the far end of a Jominy specimen and hence is equivalent to quite slow cooling. In the closed joint method, the maximum temperature during welding is below the melting point and also below the temperature at which overheating and maximum grain growth occur. The weld zone is, therefore, free from coarsened grains and from overheated metal. In the open joint method, the metal that is melted is squeezed out of the joint leaving only a thin film of fused metal. Thus, metals such as high-carbon steel and some nonferrous alloys which are notably hot-short or subject to overheating may be pressure gas welded satisfactorily. Another important factor is the absence of deposited metal. The entire weld zone is composed of base metal, and hence the properties of the weld zone are the properties of the base metals as affected by the heat of welding. This, of course, includes the effect of heat on the corrosion resistance of welded stainless steels. If unimpaired corrosion resistance is desired, stabilized alloys must be used, or the welded assembly must be heat treated after welding.

Pressure gas welds in low-carbon steels seldom require heat treatment as the heat-affected zone in such steels is usually well normalized and relatively stress-free. It has not been found desirable or necessary to stress relieve pressure-welded joints in assemblies of ordinary low-carbon steel. However, pressure gas welding has been employed on many low-alloy and high-carbon steels for fabricating assemblies subject to high service stresses and heat treating after welding has been necessary. Frequently, this heat treating may be done with the same heating heads used for welding. One important example is in rails. Here, because of the slow cooling following pressure gas welding, the metal in the annealed zone on each side of the weld may be too soft, so standard practice includes one step in which the weld zone is heated to a normalizing temperature using heating heads that are similar to those used for welding. This assures uniform heating of the rail section. Air-cooling from this normalizing temperature restores the desired hardness. Similarly, heat treatment with the welding flame has been found to be suitable for developing high physical properties in several low-alloy steels, notably when welding oil well tool joints. Such heat treatment, which is essentially a normalizing operation, recrystallizes the grains in the weld zone and tends to restore the original ductility and toughness of the metal. On the other hand, for highly hardenable steels, annealing or slow cooling after the welding operation

Table 3—Mechanical Properties of Pressure Welds

Material	Thickness	Condition	Tensile Test: Yield Point, Psi.	Tensile Test: Tensile Strength, Psi.	Tensile Test: % Elongation in 2 In.	Tensile Test: % Reduction of Area	Free Bend Test	Charpy Vee Notch Impact, Ft.-Lb.
Low-carbon steel	12-gage cylinder	As-welded	27,200	48,300	23.8	....	Flat	21.0[a]
0.20% carbon steel	1/4-in. pipe	As-welded	....	75,000	25.0	....	Flat	....
SAE 1045	1 1/4-in. diam. round	Torch-normalized	64,000	98,000	....	....	....	28.0
Rail steel	112-lb. rail	Torch-normalized	61,500	130,250	14.80	20.1	....	....
NE 8740	1-in. diam.	Torch-normalized	83,000	111,000	....	....	....	23.0
NE 8620	1-in. diam.	Torch-normalized	68,000	88,300	....	....	....	45.0
Low-alloy[b] dissimilar alloys	5-in. O.D. by 5/8-in. wall	Torch-normalized	69,000	105,900	....	....	33.0% in 1/2 in.	24.0
Stainless[c] steel to low-carbon steel	1/2 in. by 6 in.	As-welded	32,200	58,900	....	....	....	....
Stainless[d] steel to nickel alloys	3-in. diam.	As-welded	37,600	98,000	31.3	37.5	30.0% in 1/2 in.	....

[a] One third size.
[b] Grade D drill pipe and SAE 3140 steel.
[c] 12% chromium steel to 0.10% carbon steel.
[d] Silchrome valve steel to Nichrome alloy.

may be necessary to prevent hardening or surface cracking of the weld zone. However, for developing the optimum properties of welds in heat-treatable steels, furnace heat treatment is commonly used, and it has been pointed out in several literature references that the welded assemblies respond in the same manner as the original base metals.

Weld Quality

Mechanical Properties.—Since there is no deposited metal in pressure welds, the mechanical properties of good-quality welds depend upon the base metals involved. Table 3 gives typical test data taken from the literature and from some unpublished applications of pressure gas welding. In cases where dissimilar materials have been joined, the properties are most nearly those of the weaker member. The thickness and shape of the material are given in most cases and also the condition after welding.

Hardness.—The hardness of the metal adjacent to the weld is usually low because the cooling rate is low. Typical data on the hardness of pressure-welded materials are as follows (these are in the as-welded condition and so reflect the cooling rate from welding and not from any subsequent heat treatment):

Material	Size	Hardness Number
N.E. 8740	1-in. diam.	29.0 Rockwell C
N.E. 8620	1-in. diam.	17.0 Rockwell C
SAE 4340	2-in. diam.	47.5 Rockwell C
Rail steel	112-lb. rail	300 Brinell

In less hardenable steels such as low-carbon structural steel or even stainless steel or nonferrous alloys, hardening is no problem and is seldom determined.

Endurance Limit.—A number of endurance tests have been reported on pressure gas welded specimens and in some cases of full-sized welded assemblies. In most of these tests, the point of maximum loading has been placed at the weld interface and the endurance limit has been determined for 10,000,000 cycles. Typical test results are given in Table 4.

Metallography.—In pressure welds in carbon steels and many alloys, the location of the original interface is very difficult to detect when the specimens are etched with the normal etching reagents. A typical photomicrograph of a pressure weld is shown in Fig. 10. When dissimilar alloys are joined, the line of separation is clear, but under very high magnification a continuous crystalline structure

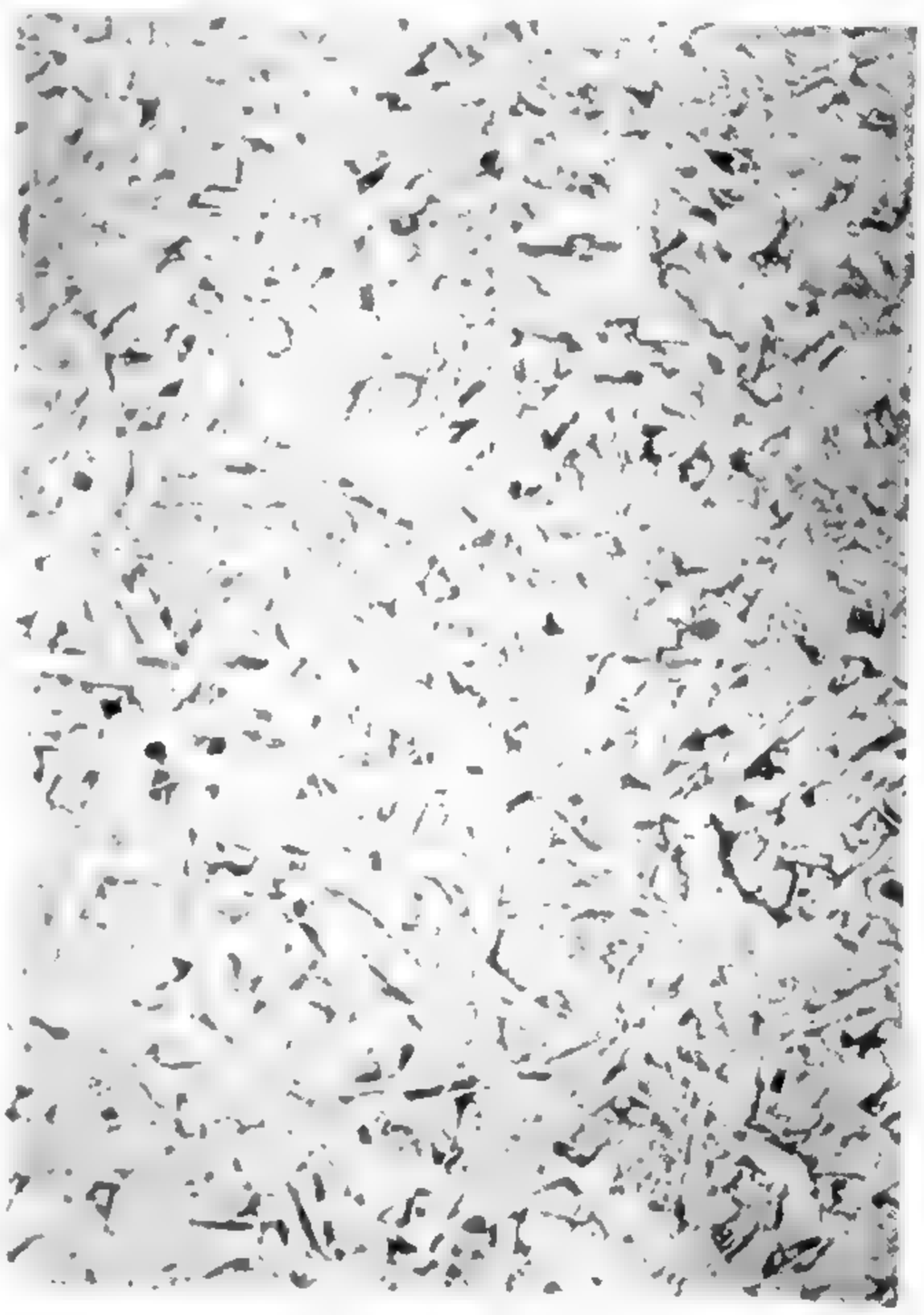

Fig. 10.—Photomicrograph of Pressure Weld in SAE 1020 Steel. The Interface Extends Vertically Through the Center of the Area Shown. As-Welded. Nital Etch. 100 ×

Table 4—Endurance Limit of Pressure Welds, 10,000,000 Cycles Of Loading

Material	Approximate Dimensions of Welded Specimen	Condition	Endurance Limit, Psi.	Endurance Limit, Tensile Strength %
Low-carbon steel plate	1/2 by 6-in. plates	As-welded	32,000	49
SAE 1045	1 3/4-in. diam. rounds	Torch-normalized	48,000	47
Rail steel	112-lb. rail	Torch-normalized	56,500	43
Stainless steel to nickel alloy[a]	3-in. diam. bars	As-welded	51,000	52
NE 8630	1/4-in. plate	As-welded	50,000	54
SAE 4340[b]	2-in. diam. rounds	Heat-treated	55,000	..
Low-alloy dissimilar materials[a]	5-in. O.D. by 5/8-in. wall tubing	Torch-normalized	50,500	47
0.25% carbon steel	8-in. diam. rounds	As-welded	34,100	..

[a] See Table 3 [b] Tested full size.

has been shown to exist. By the use of special polishing and etching techniques, it is possible to locate the line of the original weld. These etching techniques, it is claimed, disclose oxide-containing zones and these techniques have been suggested as a means of determining the quality of pressure welds.

Quality Control.—Successful pressure gas welding by the closed-joint method requires the positive and continuous control of the several factors that influence the quality of a weld. Once a pressure gas welding operation has been set up, it is necessary to control the following elements:

1. Degree of roughness and cleanliness of end preparation.
2. Maintenance of pressure cycle. Welding cycle should be completed with relatively little time variation, unit to unit.
3. Maintenance of uniformly good performance of torches.
4. Attainment of desired upset or shortening.
5. Maintenance of holding time in machine if necessary to prevent bending or warping.

The most important factors to be observed are the cleanliness of the abutting faces and the pressure-upsetting cycle. Foreign matter such as rust, dirt or oil must be removed just prior to welding, and care must be taken that the quality of end preparation and the surface contour are as required. Out-of-roundness or mismatching of pipes or tubular products is conducive to poor welding and must be corrected. In welding assemblies in which the welding flames are applied to only one face, it is essential that, if a slightly beveled end preparation is used, the open bevel face the flames. Otherwise, the weld will be of poor quality. This factor is therefore, controlled by pre-inspection of the parts themselves.

Examination of the pressure-upsetting cycle provides an excellent measure of the degree to which the welding conditions conform to the prescribed procedure. With a constant heat input into the weld zone, as indicated by constant flow of the welding gases, a constant width of heated zone and uniform pressure sequence, the entire cycle of heating and upsetting should be completed with a variation of plus or minus 5%. On this basis, if any weld requires an unduly long time or is finished too soon, examination should be made of the conditions that prevailed during the making of that weld, as this variation in time would be an indication that some factor had not been controlled properly, and hence the welded specimens would possibly be of questionable quality. Malfunctioning of the pressure system or of the heating heads or slipping of the clamps would be examples of the conditions that might cause poor-quality welds.

Autographic or other records of the pressure cycle, of the total time or time for certain stages of the procedure, of the gas flow and of the total shortening have frequently proved of great value in maintaining adequate control. These serve as visual and statistical checks on the maintenance of conditions and may be useful for preventing slight, cumulative variations that may result from manual control only.

Some of the factors described in the previous section are neither applicable to nor necessary for the open-joint method. It is unnecessary to specify the condition of the opposing faces except to assure absence of unusual amounts of foreign matter and reasonable matching. The subsequent melting of the faces offsets the need for more thorough preparation. Also, in this method the amount of upset or shortening is not necessarily constant so cannot be used properly as an index of weld quality. Due attention, however, must be given to maintenance of the pressure cycle and to obtaining good performance of the torches.

Inspection.—The first inspection is usually visual to observe the contour of the upset section and general characteristics such as presence or absence of excessive melting, irregular or non-uniform upsetting (indicative of malfunctioning of the heating head) and alignment of the weld interfaces with the center of the upset zone. In the absence of any appreciable variation from an accepted standard (previously accepted assemblies) and if assurance is provided that the controls cited have been observed, it may be concluded usually that the pressure weld is of normal quality.

If additional testing or inspection is needed, and in many highly stressed assemblies it is necessary to have added assurance of the consistency and quality of the welds, the general practice is to test destructively sample welds selected

either at random or at fixed intervals. This method has been employed in many installations and found to be quite satisfactory. It serves as a positive and continued check on the welding cycle and controls that are being used and, moreover, provides data on the properties of the welded assemblies.

None of the usual non-destructive test methods such as X-ray and supersonic testing will reveal any but large defects in pressure gas welded joints. However, magnetic particle inspection is currently being used quite successfully for the inspection of pressure-welded rails and the fluorescent penetrating oil method has been used experimentally with some degree of success.

The standard destructive weld tests are the best means of determining the quality of pressure welds. Tensile, face and root bend, nick break, Charpy and Izod impact, hardness and fatigue tests serve to evaluate pressure weld quality as in other types of welds. Of the above tests, the nick break test is one which is of importance as a convenient quality check. By fracturing a pressure weld along the original interface, the surfaces exposed show the extent of weld penetration, grain size, extent of overheating in surface metal, etc. Changes in the welding cycle can be checked quickly by this test. Experience has proved that when the nick break tests show satisfactory crystalline fractures throughout the weld cross-section, all other tests applied will usually prove satisfactory.

As an alternative to destructive testing, proof testing has been employed quite extensively, especially in pipe lines and in some automotive installations. Proof testing is designed to disclose defective welds and yet not to harm satisfactory welds. For instance, it has been the practice on pipe lines to lift the pipe line at each joint to a height of several feet, just sufficient to cause slight yielding in the weld zone. Poor-quality welds will fail under this test, but good-quality welds will satisfactorily withstand such loading. Similar methods can be developed for other welded assemblies.

A specialized inspection method has been developed for applications which justify considerable attention to inspection procedures. In this method, a flat, thin, continuous chip is machined from the inner or outer surface of the weld zone and treated with special etching reagents which disclose the presence or absence of an oxidized interface. In this manner, it is possible to determine whether the weld is of good quality for the full thickness, without subjecting the weld to proof testing. (See Chapter 42 for further information on standard test methods.)

EQUIPMENT USED

Machines

The apparatus for pressure gas welding comprises equipment for applying end pressure, suitable welding heads designed to provide uniform and controlled heating of the weld zone and the necessary indicating and measuring devices for regulating the process throughout its cycle of operation. The complexity or simplicity of the machine obviously depends on the configuration and size of the parts being welded and on the degree to which the process is mechanized. In most cases, it has been found advisable to design and construct special apparatus for gripping the parts and applying the welding pressure, and to use special heating heads. There are, however, machines available that are adaptable to welding a rather wide range of shapes and sizes of elongated stock.

Examples of typical equipment for pressure gas welding are shown in Figs. 11, 12 and 13. Figure 11 illustrates the simplest manually operated and controlled device. This machine is capable of handling bars and tubes up to 3 in. in section. Interchangeable heating heads and equipment for making this process almost fully automatic are available. Figure 12 illustrates a more complex machine that is especially designed for welding rails. The rails are gripped by sidewise pressure acting through angle bars, and the heat is supplied through specially shaped heads conforming in shape to the rails. The welding control is partly manual. Figure 13 illustrates a machine specially designed for pressure welding overland pipe.

Auxiliary Equipment

Some auxiliary equipment is necessary. The gas supply must be adequate for the maximum flow requirement, and the gas

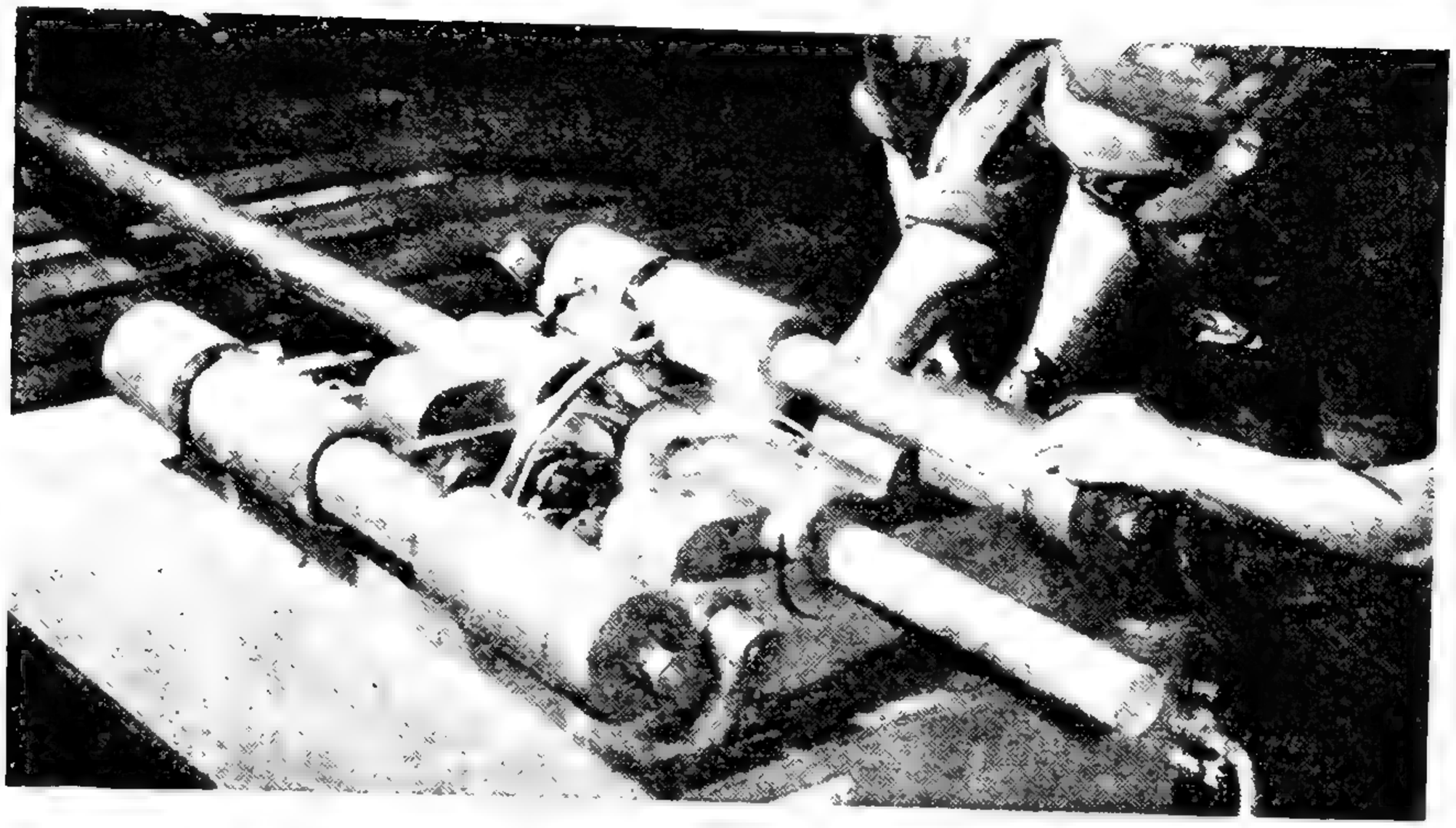

Fig. 11.—Small Portable Machine for Welding Bars, Tubes and Structural Shapes Up to About 3 In. in Section. The Machine Is Essentially Manually Operated

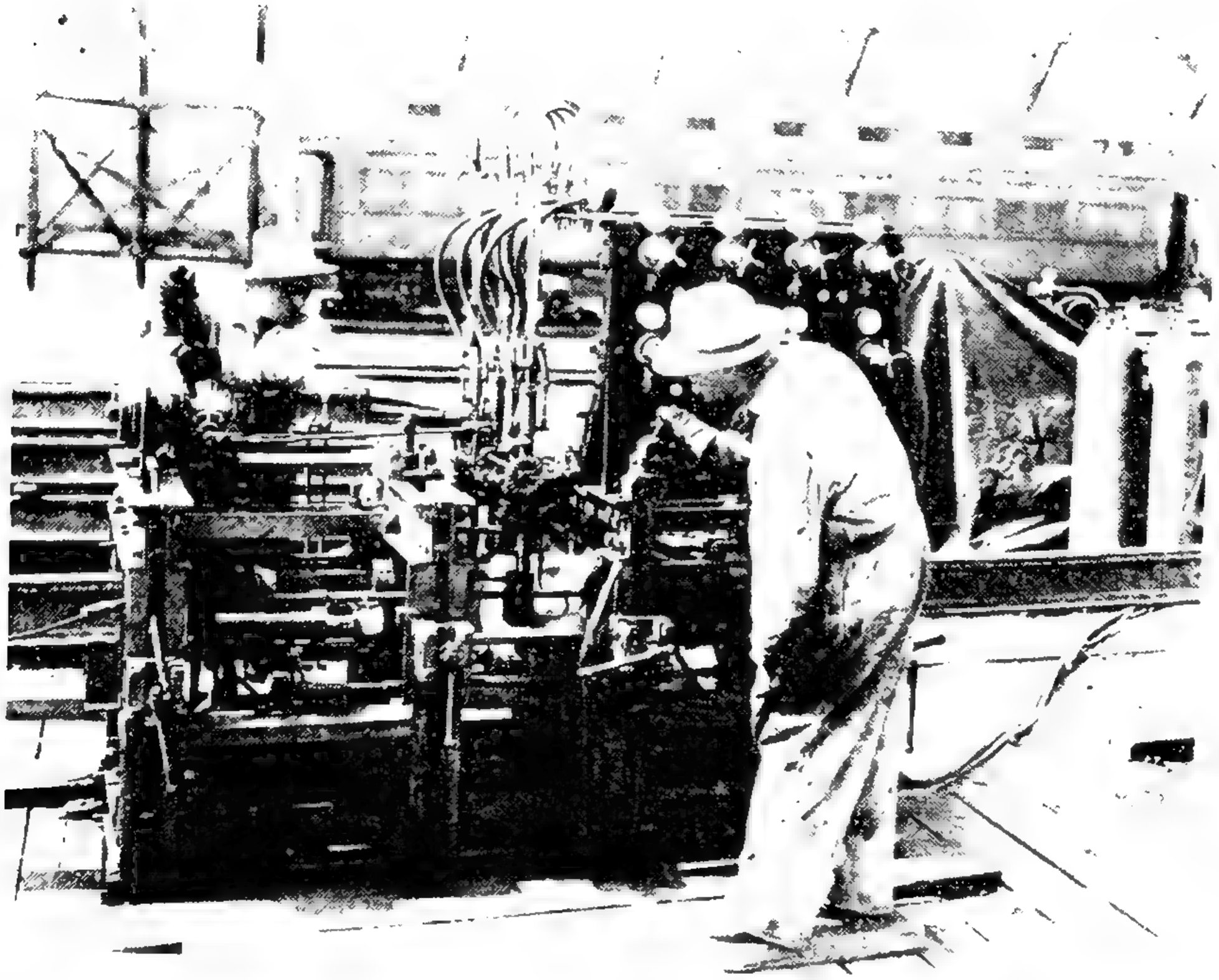

Fig. 12.—Special Machine Designed for Welding Continuous Lengths of Railroad Rail. Machine Provides Special Side-Gripping Clamps and Oscillating Support for 4 Heating Heads. Apparatus Is Actuated by Hydraulic Pressure

regulators must be capable of maintaining a uniform flame with slight feather of excess acetylene. As the process is often at least partially mechanized, quick-acting shutoff valves are very desirable, and, in many instances, needle valves are advantageous for providing fine adjustments of the flame ratio. The best control of the gas flow, hence heat input, is obtained when the gages indicating the pressure on particular heads are located on the machine. This permits ready checking by the operator. In some installations, flowmeters have been used as an added means of obtaining uniform gas flow.

An ample supply of cooling water is also needed for cooling the torches and, in some cases, for cooling the clamps and parts of the press. Adequate jigs for aligning and supporting the specimens are sometimes needed, and automatic control units for regulating the pressure and heating cycles and discontinuing the operation when the weld is completed are available. This additional apparatus makes the process almost completely automatic.

COMMON APPLICATIONS

Materials

Pressure gas welding has been successfully applied to steels over a full range of carbon content, to low-alloy and high-alloy steels, and to several nonferrous metals such as Monel, nickel-chromium and copper-silicon alloys. It has been especially advantageous for joining dissimilar metals. The following typical applications exemplify the range of the process in respect to type of product and materials.

Pressure-Welded Rails

Pressure gas welding of railroad rails was the first commercial application of the process (1938). Since then, over 60,000 pressure-welded joints have been made in rails of all the standard weights. The general practice is to pressure-weld the rails in strings of from three to twelve rail lengths depending upon the intended use. In cases where longer lengths of continuous rail are needed, tie-in welds are made in track by gas weld-

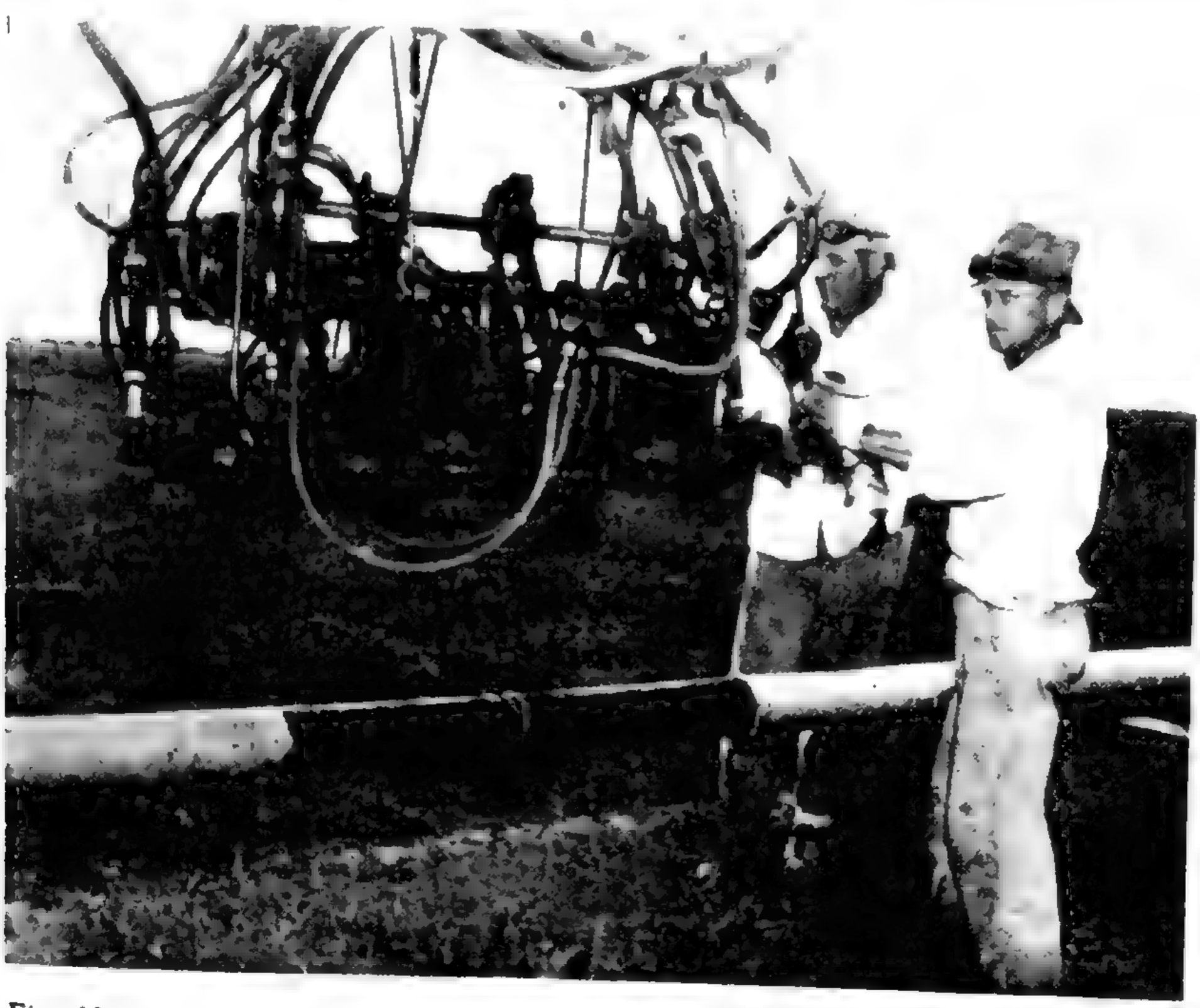

Fig. 13.—Clamp for Welding 6-In. Overland Pipe. Machine Clamps and Aligns Pipes and Supports a Split Annular Heating Head Which May Be Oscillated Manually

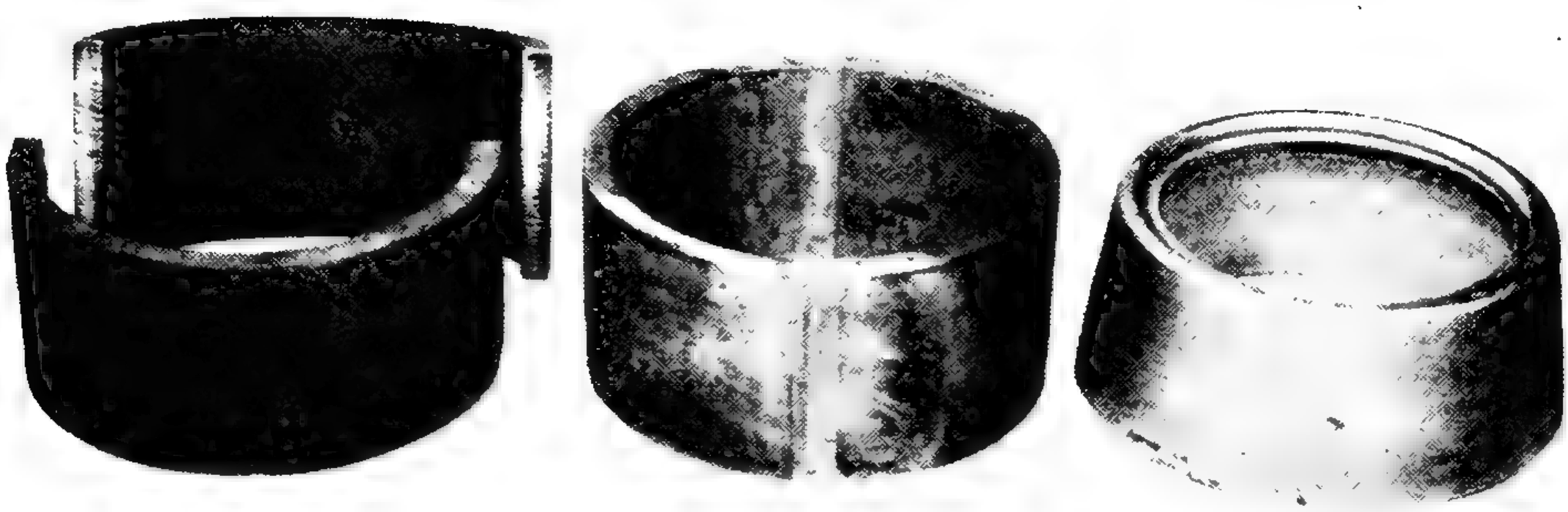

Fig. 14.—Three Steps in Welding Rings of Stainless Steel. The Forming Required to Produce the Conical Ring on the Right Serves as an Excellent Non-Destructive Test of the Weld Quality

ing. Many installations have been in tunnels, station platforms, bridges and cross-overs, but a considerable amount of continuous rail has been laid in tangent track in lengths of over 1000 feet. A typical machine for such welding is shown in Fig. 12 and the general welding procedure is as follows: The rail ends are carefully prepared by power-sawing, cleaned and butted under a constant pressure of about 2800 psi. The rails are gripped by special clamps, and heat is applied by means of four specially shaped heating heads which are oscillated automatically through the desired stroke. On the completion of the welding cycle, the rails are moved one rail length and the upset metal on the ball and edges of the base removed by oxygen-cutting. In the next position, the weld zone is torch-normalized to refine the grains and restore a normal hardness to the weld zone. Finally, when cold, the weld is ground to smooth contour, examined by magnetic particle inspection, and oiled for protection against rusting. Rails welded, normalized and inspected in this manner have an endurance limit at 2,000,000 cycles of more than 77 percent of unwelded rails, and have given very satisfactory service under both heavy and fast traffic over extended periods of time, ex-

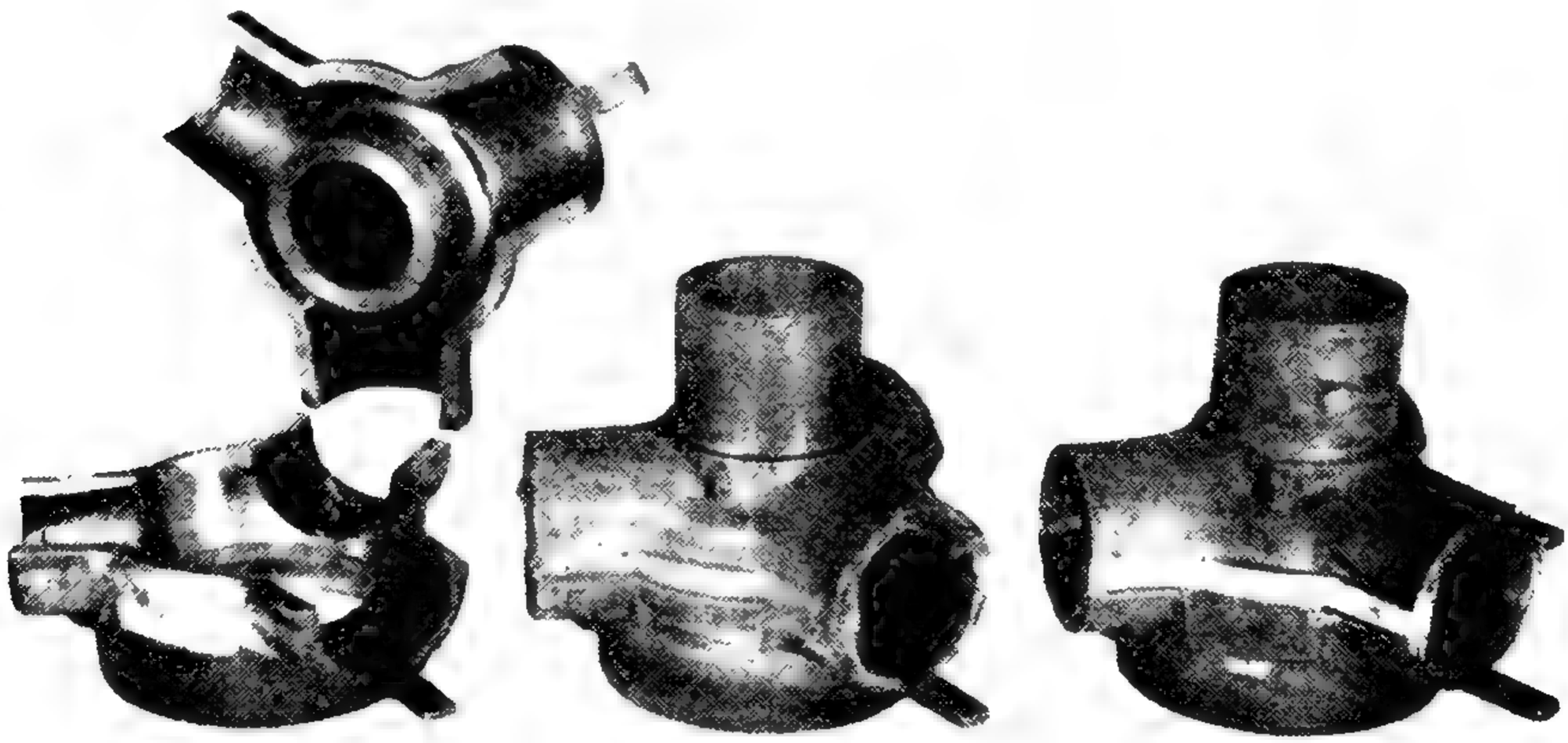

Fig. 15.—Forged Aircraft Propeller Barrel Halves, Machined and Ready for Welding, Are Shown at the Left. The Assembly Immediately After Welding Is Shown at Center. The Heat-Treated Assembly with Weld Upset Removed, Is Shown at the Right

tending up to nine years for some installations. The use of pressure gas welded rails has resulted not only in smoother riding quality in the track but in reduced maintenance-of-way costs.

Overland Pipe Lines

Pressure gas welding was introduced for joining overland pipe lines in 1941. Since then, over 1800 miles of high-pressure pipe lines for oil, natural gas, water, helium and propane have been welded in the United States, Mexico and Russia.

Fig. 16.—Four Steps in Welding High-Speed Steel Drill Bit to Low-Carbon Steel Shank for the Manufacture of Core Drills

These lines have ranged from 2 to 24 in. in diam. and have been laid in the progressive or stove-pipe manner using special clamping jigs for use in the field. Photographs of typical apparatus for this application are shown in Fig. 13.

Typical operating data for pressure welding are as follows:

Initial pressure: 1000 psi. of pipe cross-section
Final pressure: 4000 psi. of pipe cross-section

Wall Thickness, In.	Welding Time, Sec.	Total Shortening, In.	Pipe End Bevel, Deg.
0.187	45	0.25	4
0.203	50	0.265	4
0.238	55	0.300	4
0.250	60	0.312	5
0.375	90	0.412	6

Stainless Steel Rings

Figure 14 shows the steps for pressure gas welding and forging of rings of types 347, 321 or 310 stainless. For welding these alloys, the quality of end preparation and the pressure cycle are very important. The die forging operation needed to produce the desired shape is an excellent proof test of the welded assembly. These stainless steel rings have been used as components of aircraft gas turbines and give excellent service.

Aircraft Propeller Barrels

High-strength aircraft propeller barrels of SAE 4345 alloy steel have been successfully fabricated by pressure gas weld-

ing two forgings to form the assembly. Specified minimum tensile properties of the assemblies after heat treatment are as follows: yield strength (0.2% offset) 115,000 psi.; tensile strength 135,000 psi.; elongation in 2 in., 8%; reduction of area 35%. The closed-joint method employing a multiple pressure cycle was used.

The sequence of operations arrived at in producing these barrels is shown in Fig. 15. The two forgings machined and made ready for welding are shown at the left. The assembly immediately after welding is shown at the center, and at the right after upset had been removed and the assembly heat treated.

Immediately after welding and before the heated area has cooled to below 600° F., the assemblies are transferred to a stress-relief furnace at 1200° F. for six hours and then air-cooled. This is necessary as the steel is air-hardening in the section sizes used, and stress cracks result on air-cooling from welding temperatures.

Landing Gears

Pressure gas welding has been used successfully in the fabrication of landing gear assemblies. For this, butt welds have been made between tubes ranging in diameter from $2^{7}/_{8}$ to 16 in. with wall thickness ranging, respectively, from $^{1}/_{4}$ to 1 inch. The tubes are NE 8740 and NE 8630 steel, heat treated after welding to attain a tensile strength of 180,000 to 200,000 psi. Welding was done under closely controlled conditions and inspected by the etching procedure described previously.

Miscellaneous

The miscellaneous applications point most clearly to the adaptability of the process. A typical application is the joining of a 2-in. long, 2-in. diam. tool steel bit to a low-carbon steel shank. This was done primarily to conserve alloy steel, but it serves as an excellent example of the use of the process for joining materials of markedly different mechanical properties. The photographs shown in Fig. 16 illustrate the several steps in this welding operation. The welding cycle was about two minutes.

Fig. 17.—Pressure Gas Welded Axle Housing of S.A.E. 1045 Steel in As-Welded Condition. Flat Surface of Upset Zone Resulted from Original Bevel Preparation

The safe-ending of boiler tubes is done in the machine shown in Fig. 11 (time, about one minute). A somewhat larger application is illustrated in Fig. 17. This is the fabrication of automotive axle housings which are assembled from SAE 1045 steel. The material at the weld is $3^{3}/_{4}$ in. O.D. by $^{9}/_{16}$ in. wall thickness. The total welding time is $2^{1}/_{8}$ minutes with gas consumption of 7 cu. ft. per weld. The process is also in use for repair welding of 8 in. diam. hammer rods of SAE 2330 steel, an operation which takes about 30 min. welding time and requires about 550 cu. ft. of oxygen per joint. This application, although large, is amply justified by the reclamation of large forgings which would be very expensive to replace otherwise. Subsequent service experience with pressure gas welded hammer rods has been very satisfactory.

BIBLIOGRAPHY

1. *New Oxy-Acetylene Process for Butt Welding Rails,* L. Adams, Railway Engineering and Maintenance, January 1939.

2. *Oxy-Acetylene Pressure-Welding of Railroad Rails,* L. Adams, The Welding Journal, November 1941.

3. *Pressure-Welding of Pipe Lines,* A. L. Forbes, Petroleum Engineer, March 1943.

4. *Pressure-Welding of Heavy Tubing,* W. G. Wood, Iron Age, September 23, 1943.

5. *Fatigue Strength of Welded Aircraft Joints,* T. V. Buckwalter, and O. J. Horger, The Welding Journal Res. Suppl., January 1944.

6. *Oxy-Acetylene Pressure-Welding,* A. R. Lytle, The Welding Journal, December 1944.

7. *Solid Phase Welding,* A. B. Kinzel, The Welding Journal, December 1944.

8. *Application of Pressure-Welding to Manufacture of Aircraft Landing Gear,* E. R. Proctor, The Welding Journal, November 1945.

9. *The Application of Pressure Welding to Overland Pipe Lines,* E. P. Jones, The Welding Journal, January 1946.

10. *Metallurgical Aspects of High Quality Pressure-Welded Joints for Landing Gear—Parts I & II,* Leslie Fine, C. H. Maak, and A. R. Ozanich, Metal Progress, February and March 1946.

11. *Pressure-Welding's Flexibility Solves Alloy Pipe Problems,* E. P. Jones, Oil and Gas Journal, September 21, 1946.

12. *Oxy-Acetylene Pressure-Welding of Some Low-Alloy Steels and Non-Ferrous Alloys,* K. H. Koopman, The Welding Journal, November 1946.

13. *Pressure-Welding Stainless Steel Rings,* A. L. Rustay, A. Crowell, S. M. Jablonski, and C. J. Burch, The Welding Journal, February 1947.

14. *Mechanical Properties and Microstructures of Open-Butt Oxy-Acetylene Compression Welds,* H. H. Chiswik, The Welding Journal, February 1947.

15. *Pressure-Welding Propeller Barrels,* G. W. Motherwell, A. L. Rustay, S. M. Jablonski, and C. J. Burch, The Welding Journal, November 1947.

16. *Multiple Flame Pressure-Welding Process,* N. H. Cuke, The Welding Journal, January 1948.

CHAPTER 8

ARC WELDING EQUIPMENT AND MATERIALS*

A. SHIELDED METAL-ARC WELDING MACHINES

ALTERNATING - CURRENT ARC-WELDING MACHINES

General

ALTERNATING-CURRENT arc-welding machines have been made both in single-operator and multiple-operator, static transformer styles and as rotating equipment. Practically all units in use are of the single-operator, static transformer type. This equipment has a volt-ampere characteristic approaching the constant current form. Figure 1 has typical characteristic curves of a 300-amp. a.c. welding machine and shows the effect of power-factor-correcting capacitors on the shape of the power factor and current input curves. The leading current drawn by the capacitors balances the lagging component of the transformer of the primary current at about one-half load making the power factor unity at this point. Multiple operator units have constant voltage characteristic and require a ballast resistor or reactor for each welder in order to regulate the current delivered to the arc.

Alternating-current arc-welding machines of the transformer type are usually made in ratings which have been standardized by the National Electrical Manufacturers Association, as listed in Table 1. Machines having ratings of 500 amp. and over are mainly used for machine welding with automatic welding heads.

For manual arc welding in industrial plants, machines having 200-, 300- and 400-amp. ratings find the widest application. Electrodes in diameters as small as $^{1}/_{16}$ in. may be used with 200-amp. machines and electrodes over the range of $^{1}/_{8}$ to $^{5}/_{16}$ in. with the 400-amp. machines.

Machines having a 150-amp. rating find their largest application in light industrial and in garage and job-shop welding.

In addition to the ratings shown in Table 1 there are two other ratings developed primarily for use by farmers on REA* lines. These two ratings, shown in Table 2, have their primary input current limited to a definite value so that a 130-amp. rated machine without power factor correction and a 180-amp. rated machine with power factor correction may operate satisfactorily from 3-kva. REA transformers.

Parallel Operation.—Single - operator, a.c. arc-welding machines which have the same no-load voltage may be operated satisfactorily in parallel, in order to get more current per arc than either will give separately. Care must be taken when connecting two transformers together that they are both connected on the primary side to the same phase of the same power supply. Care must also be taken that the voltages produced by the secondaries are in phase and not opposite each other. Paralleling a.c. welding machines requires their connection to the same phase of the power line and with the same polarity. This is checked before connecting the electrode leads (*B*) together (Fig. 2) by measuring the voltage between them after the primary windings are energized. The voltage should read close to zero. If it reads double normal

* Prepared by a committee consisting of R. F. Wyer, General Electric Co., *Chairman;* J. H. Blankenbuehler, Hobart Brothers Co.; E. E. Tisza, Air Reduction Sales Co.; Martin Rebuffoni, Westinghouse Electric Corp.

* Rural Electrification Administration

Table 1—Ratings of A.C. Arc-Welding Machines

Current, Amp.	Load Volts	Duty Cycle, %	Minimum Current and Load Voltage		Maximum Current at Rated Load Voltage, Amp.[a]	Duty Cycle at Max. Current and Rated Load Voltage, %[a]
	Rating		Amp. at	Load Volts	Welding Current Range	
1	2	3	4	5	5	6
150	30	50	20	20	185	30
200	30	50	30	20	250	30
200	40	60	40	20	250	35
300	40	60	60	20	375	35
400	40	60	80	20	500	35
500	40	60	100	20	625	35
750	40	1 hr.[b]	187	30	935	..
1000	40	1 hr.[b]	250	30	1250	..

[a] Welding machines may be operated at the current shown in Column 5 and the duty cycle shown in Column 6 at rated-load volts with approximately the same temperature rises as those specified for the rated amperes and duty cycle (Columns 1 and 3).

[b] These sizes are rated for service with automatic machines. In testing to determine the rating, temperature rise and other characteristics, rated current at rated-load voltage is applied for 1 hr. immediately followed by the application of 75% rated current at rated-load voltage for 3 hours. The temperature rise is measured at the end of the 1-hr. period and at the completion of the 3-hr. period.

NOTES: (1) Load voltage is the voltage between the welding terminals of the welding machine when current is flowing. (2) In arc welding duty cycle is defined as the ratio of arc time to total time. For the purpose of standard rating, the time period of one complete test cycle is 10 minutes. For example, in the case of a 60% duty cycle, load is applied continuously for 6 min and shut off for 4 minutes. Load must not be applied for more than 6 min. out of any 10-min. period.

voltage, the polarities of the machines are opposite, and the primary connections of one or the other must be reversed.

Alternating-current welding machines having power factor correcting capacitors connected across their primary windings should be connected to the power line through a single disconnect switch. This is to prevent the possibility of opening the primary circuit of one welding machine while the other is energized. If this precaution is not taken, the disconnected welding machine will be excited through its secondary by the other unit. Excessive resonant voltages may be generated by the combination of reactance and capacity in the primary circuit.

Power Supply.—Single-operator a.c. arc-welding machines are single-phase units made for 220-, 440- or 550-volt power supply and for 25, 50 or 60 cycles. Some of the multiple-operator transformer units are arranged for polyphase operation. The installation of large single-operator, a.c. welding machines in small shops or on a power line with limited capacity will result in an unbalanced load on the three-phase power supply. In a majority of cases, however, large sizes are only used where the power supply is ample. Where a considerable number of units are being installed they can frequently be connected to different phases, practically eliminating seriously unbalanced line loads.

Practically all a.c. welding machines are now equipped with power-factor-correcting capacitors and are generally arranged to have a power factor of about 80% lagging at rated load. (Single-operator, a.c. welding machines without power-factor-correcting capacitors have an average power factor of about 30%.) This amount of power factor correction will result in an increasing power factor with decreasing loads until unity power factor is reached at about half load. At loads below half load, the unit will have a

Table 2—Ratings for Limited Input Welding Machines

Rated Load, Amp. (Maximum Obtainable at Rated Load Volts)	Rated Load Volts	Duty Cycle, %	Minimum Welding Current, Amp.	Welding Machines with Power-Factor Correction[a], Amp.	Welding Machines Without Power-Factor Correction[a], Amp.
1	2	3	4	5	6
130	25	20	20	27	33
180	25	20	20	37	46

[a] Current input at rated-load amperes (Column 1) and rated-load volts (Column 2) not to exceed these values.

leading power factor. At no load, these welding machines generally have approximately 3 kva. of power-factor-correcting capacity per 100 amp. of their rating.

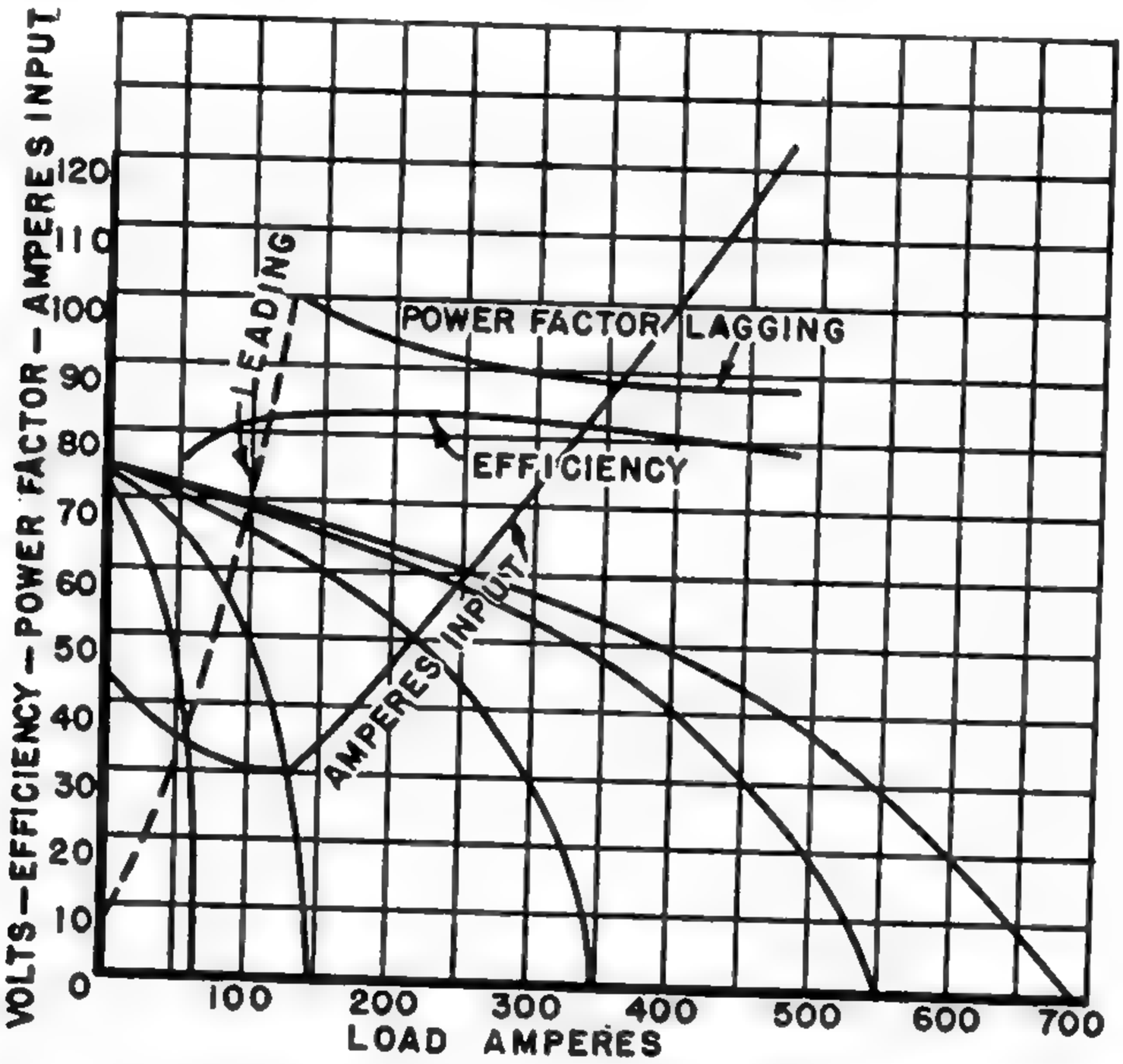

Fig. 1.—Typical Characteristic Curves of 300-Amp. Welding Transformer

The no-load power input of transformer-type, a.c. welding machines is very low, particularly when compared to single-operator, motor-generator machines. A single-operator, a.c. welding machine will draw from 100 watts to 1000 watts at no load, depending on its rating and whether it is fan cooled or naturally ventilated. Naturally-ventilated units will have a no-load input of about 50 watts per 100 amp. of rating; fan-cooled units will have a no-load input of roughly 150 watts per 100 amp. of rating.

Single-operator, a.c. welding machines have a specially high load efficiency, usually between 80 and 90%. The combination of high full-load efficiency and low no-load input makes the power consumption of transformer-type, a.c. welding machines much less than that of motor-generator sets of comparable rating.

Open-Circuit Voltage.—The arc stability of an a.c. welding machine in which the current is controlled by reactance depends almost entirely on the no-load voltage, although the use of small capacitors in shunt with the secondary provides an additional stabilizing effect. The no-load voltage of the transformer also affects its physical size and the relative safety of the welder. It is natural, therefore, that great effort has been expended in developing welding electrodes to be used on lower and lower voltages. At present, a.c. machines are available with no-load voltages from 40 to as high as 150 volts. The NEMA standards require that the no-load voltage not exceed 80 volts for manual welding and 100 volts for machine welding.

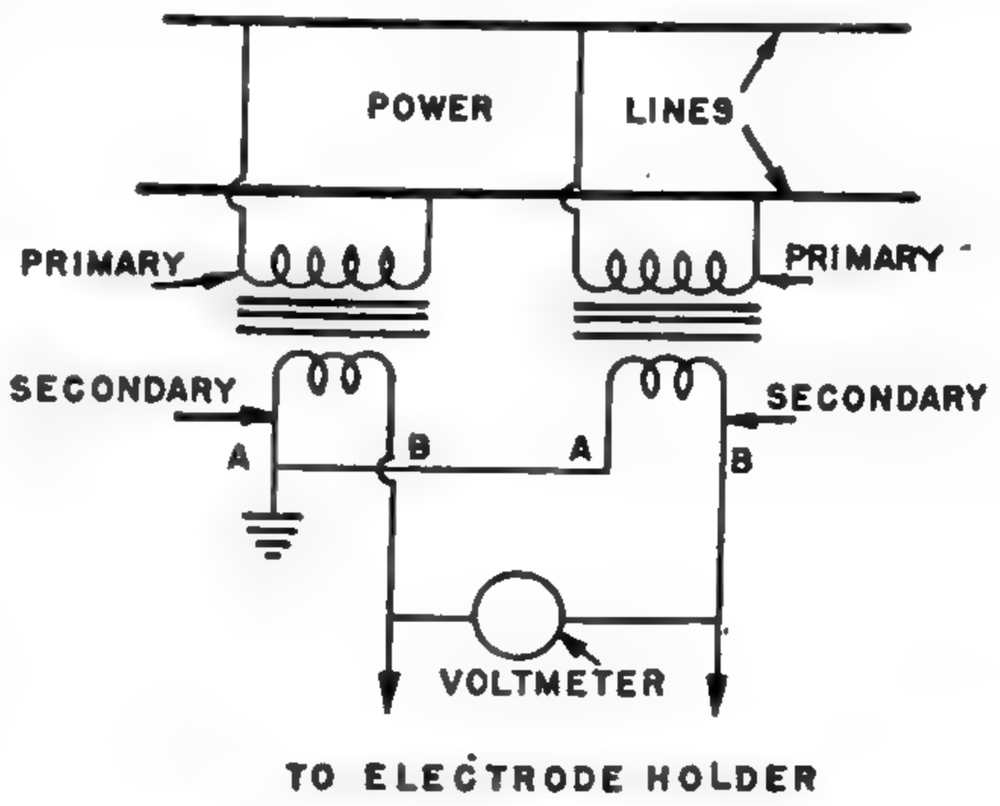

Fig. 2.—Method of Checking Connection of Parallel-Connected A.C. Welding Machines

No load voltages of 65 and 75 volts are usual for a.c. welding machines of industrial sizes. In smaller sizes, such as the limited-input type mentioned above, voltages do not exceed 65 and in some cases go as low as 40 volts. Almost any type of a.c. electrode may be used with a 75-volt, a.c. welding machine, whereas machines of lower voltage may require the selection of particular grades and types of electrodes for successful service unless a stabilizing circuit is used.

Control Devices.—Safety controls are available which reduce the idling voltage of a.c. arc-welding machines so that the voltage at the electrode holder during no-load periods is automatically reduced to a low value, generally about 30 volts. These devices consist of relays and contactors which either reconnect the main winding of the transformer for a lower voltage, or disconnect the welding load from the main transformer and connect it to an auxiliary transformer of a lower voltage.

particularly at current levels below 100 amperes.

The industrial sizes of a.c. arc-welding machines may generally be equipped with a remote-control device, usually motor-driven, which may be used to adjust the welding input current of the unit from a remote position.

Principles of Operation

Single-operator, a.c. arc-welding machines may be divided into three general classes with respect to the means employed to control the output current. Two of these classes use a constant voltage transformer and control the output current by means of an adjustable resistor or an adjustable reactor (Fig. 3) in the output circuit of the transformer. The adjustable resistor is rarely used; the adjustable reactor is frequently used. The third class includes those welding machines in which the internal reactance of the transformer is adjustable.

Adjustment of separate reactors may be

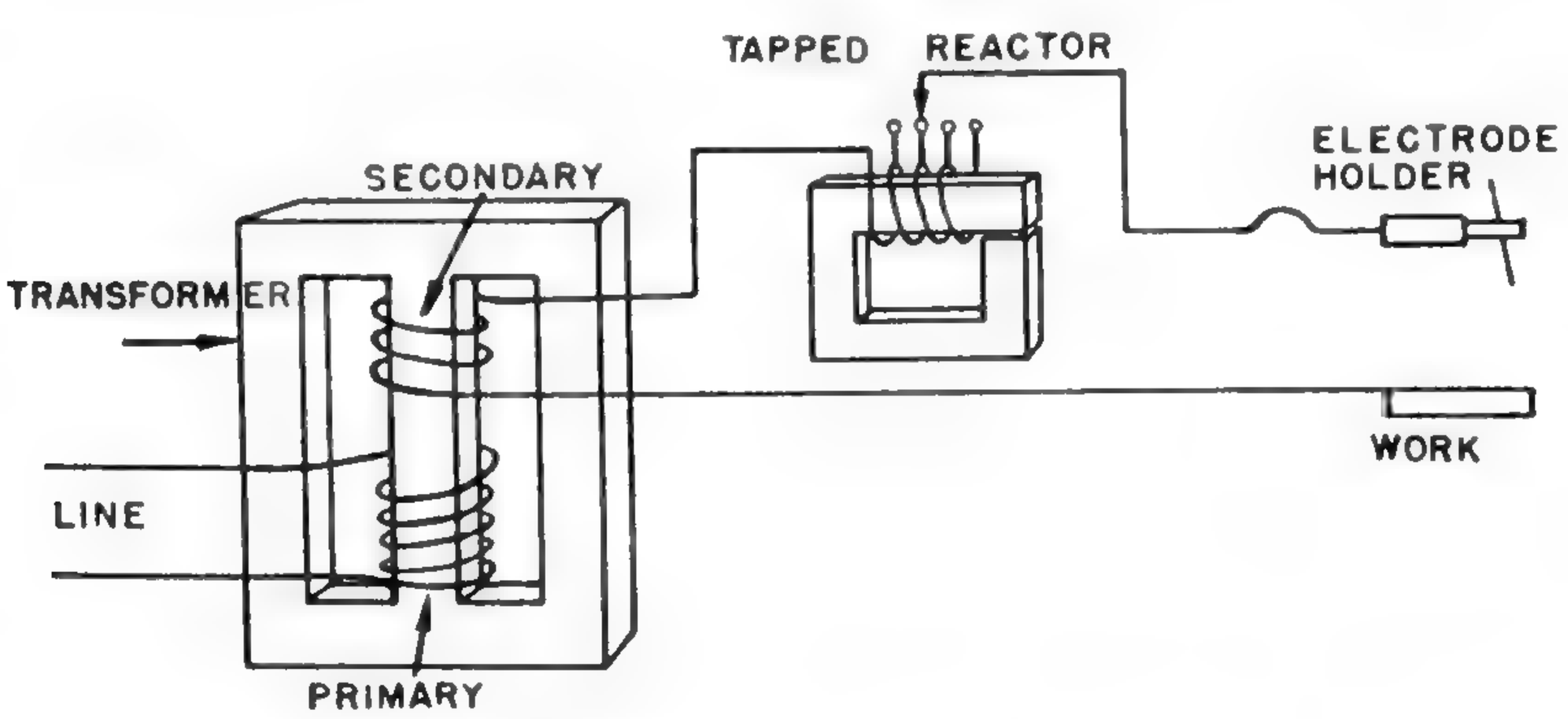

Fig. 3.—Constant Voltage Transformer with Tapped Reactor Coil

Primary contactors or switches are not usually included in the larger a.c. machines for industrial use which are used for manual welding. The small, limited-input welding machines are generally equipped with a manually-operated primary switch.

Some a.c. welding machines incorporate a system of relays which operate to deliver a much higher than normal current to the arc for a fraction of a second at the start of the weld. This device is intended to give starting surge characteristics similar to those of d.c. welding machines and to facilitate striking the arc,

by means of plugs or switches, making connections to taps on the reactor winding. Another method of adjusting the reactance is by means of an adjustable air gap in the magnetic circuit of the reactor (Fig. 4). Continuous adjustment of the output current, without definite steps, can be obtained by a crank and screw moving an iron block to vary the air gap and thus the reactance of the coil. Another method of varying the effective reactance of a reactor is to saturate its magnetic circuit by means of a direct current winding on the center leg of the reactor (see Fig.

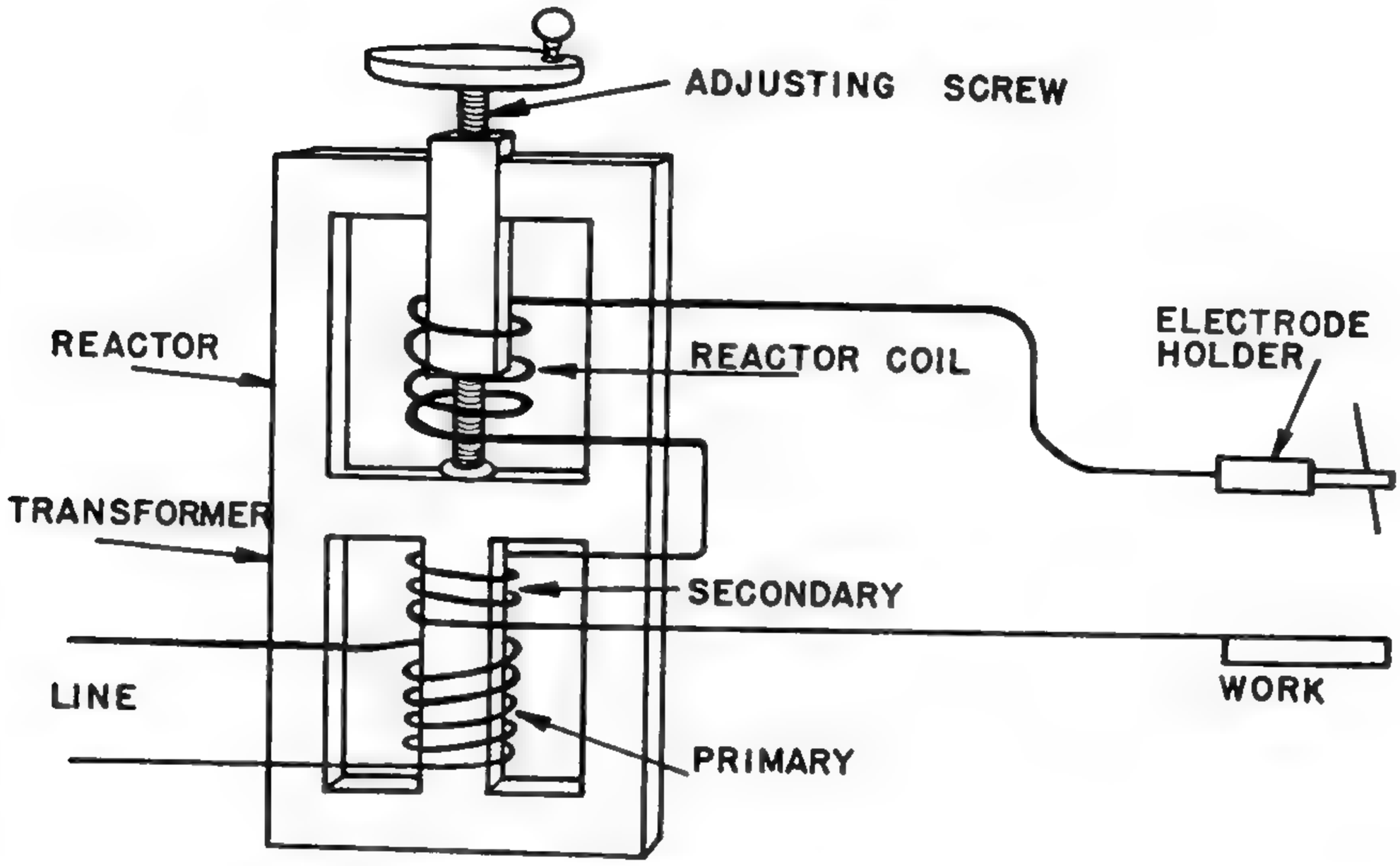

Fig. 4.—Constant Voltage Transformer with Magnetically Adjustable Reactor

5). Direct current may be provided by a rectifier energized by connections to the main transformer. Adjustment of a rheostat will vary the direct current. the saturation of the iron core of the reactor, thus controlling the output.

In welding machines having the current-limiting reactance built into the main transformer, adjustment may be accomplished by changing the position of the primary and secondary coils with respect to each other (Fig. 6) or by means of a movable iron member in the magnetic circuit (Fig. 7). Separating the coils further, or shortening the air gap, increases the leakage flux between the coils and reduces the output current.

Since it is reactance in the secondary current of the welding-machine transformer which controls the welding current level, it is evident that the reactance of the output cables will affect the welding current adjustment. Long leads which are widely separated, particularly if they

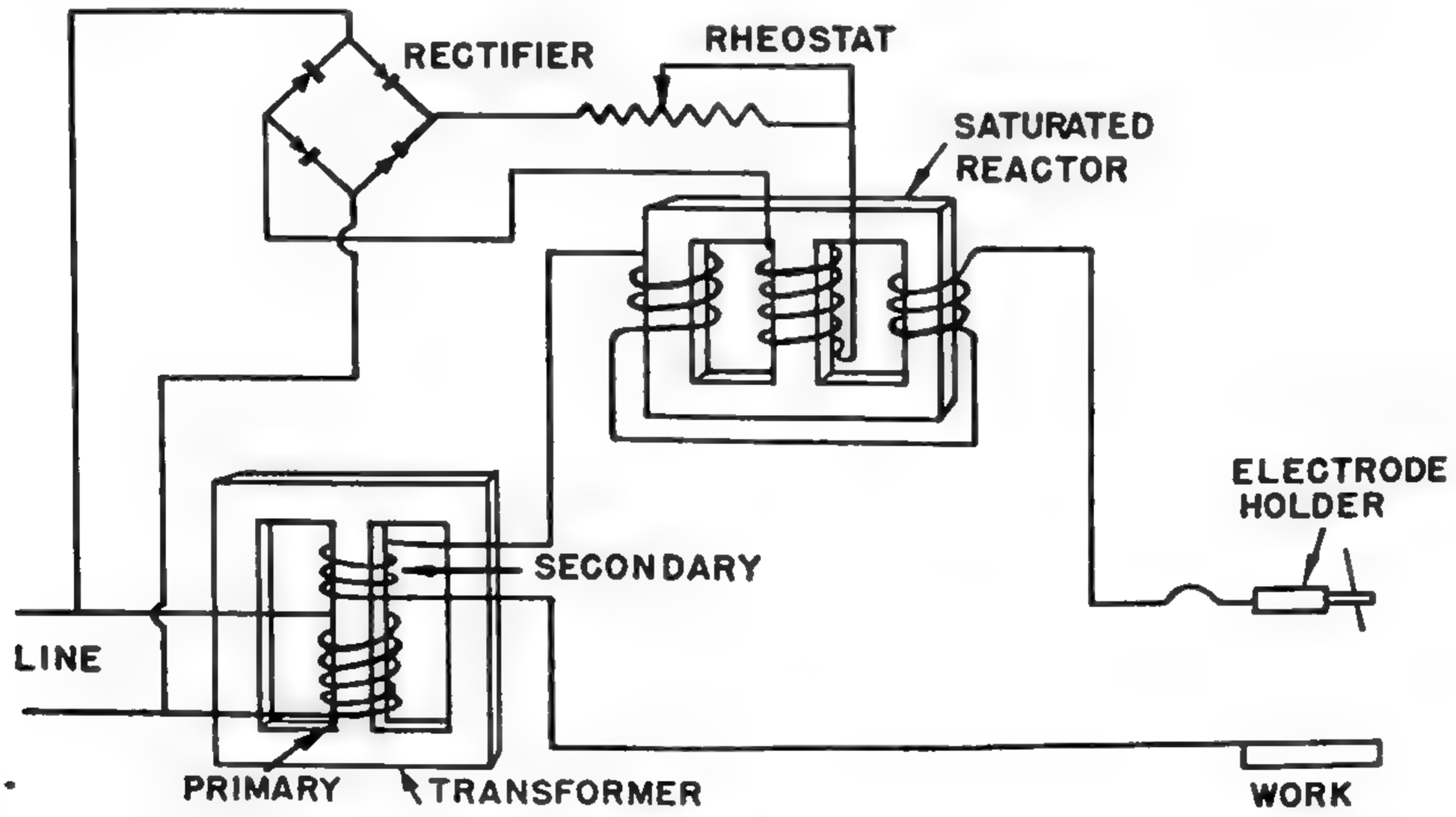

Fig. 5.—Constant Voltage Transformer with Electrically Adjustable Reactor

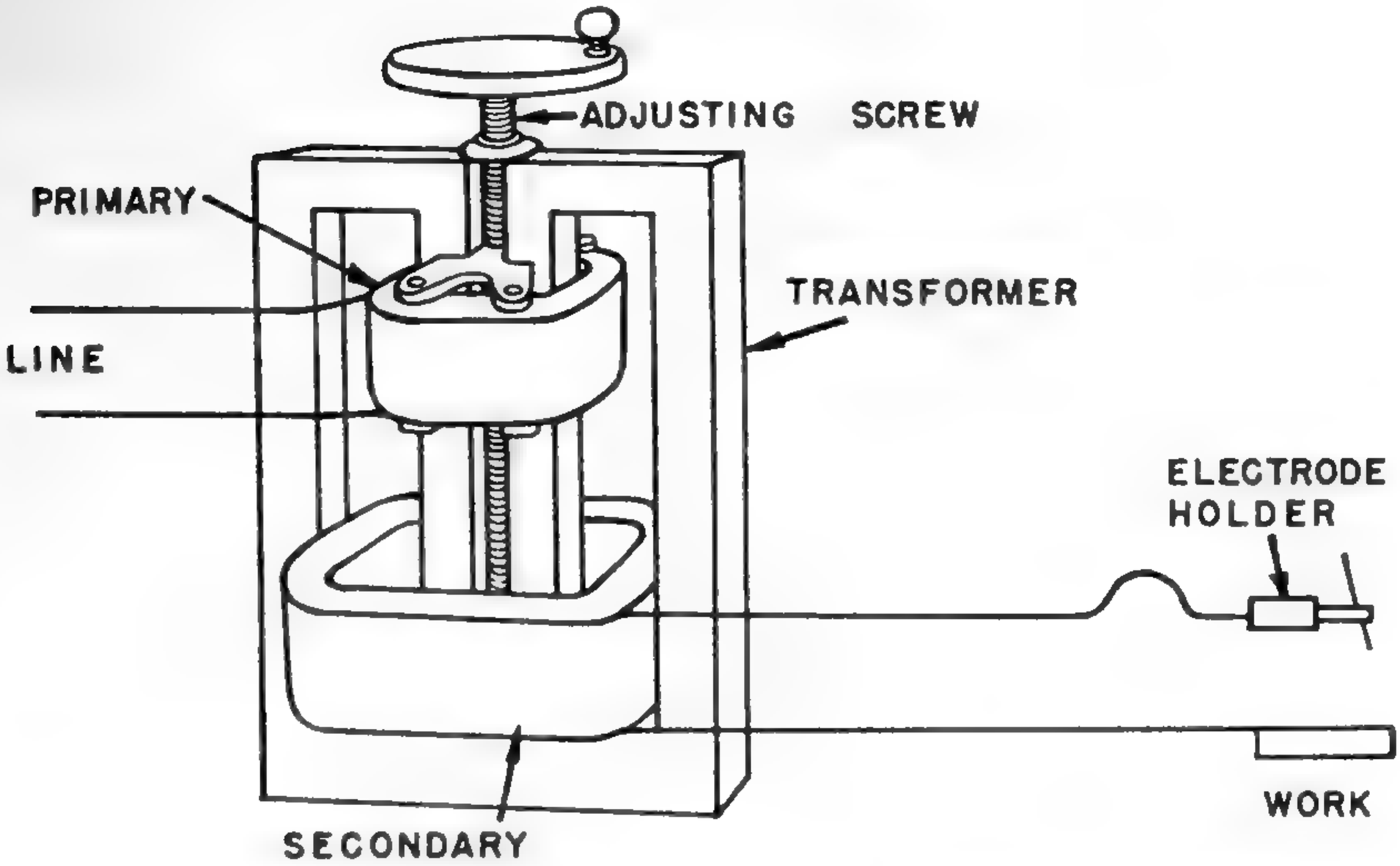

Fig. 6.—Constant Current Transformer with Adjustable Coil Spacing

lie upon iron or steel floors, increase the reactance of the welding circuit and reduce the current output of the welding machine. Electrode and work leads should be as short as possible and, where practical, should lie close together. On account of the reactive voltage, the total voltage drop in the leads will be greater in an a.c. circuit than in a d.c. circuit with similar lead arrangement. In both cases, the major effect is to reduce the maximum output of the welding equipment, and it is only rarely that this becomes important.

Installation

Installations of welding machines should meet applicable requirements of the *National Electrical Code* and local codes. Welding machines should be located in a clean, dry place and should not rest on a dirt floor. They should be protected from undue exposure to the weather when located out of doors. The case of the machine should always be well grounded, using the grounding lug provided. Care should be taken to bush the primary leads

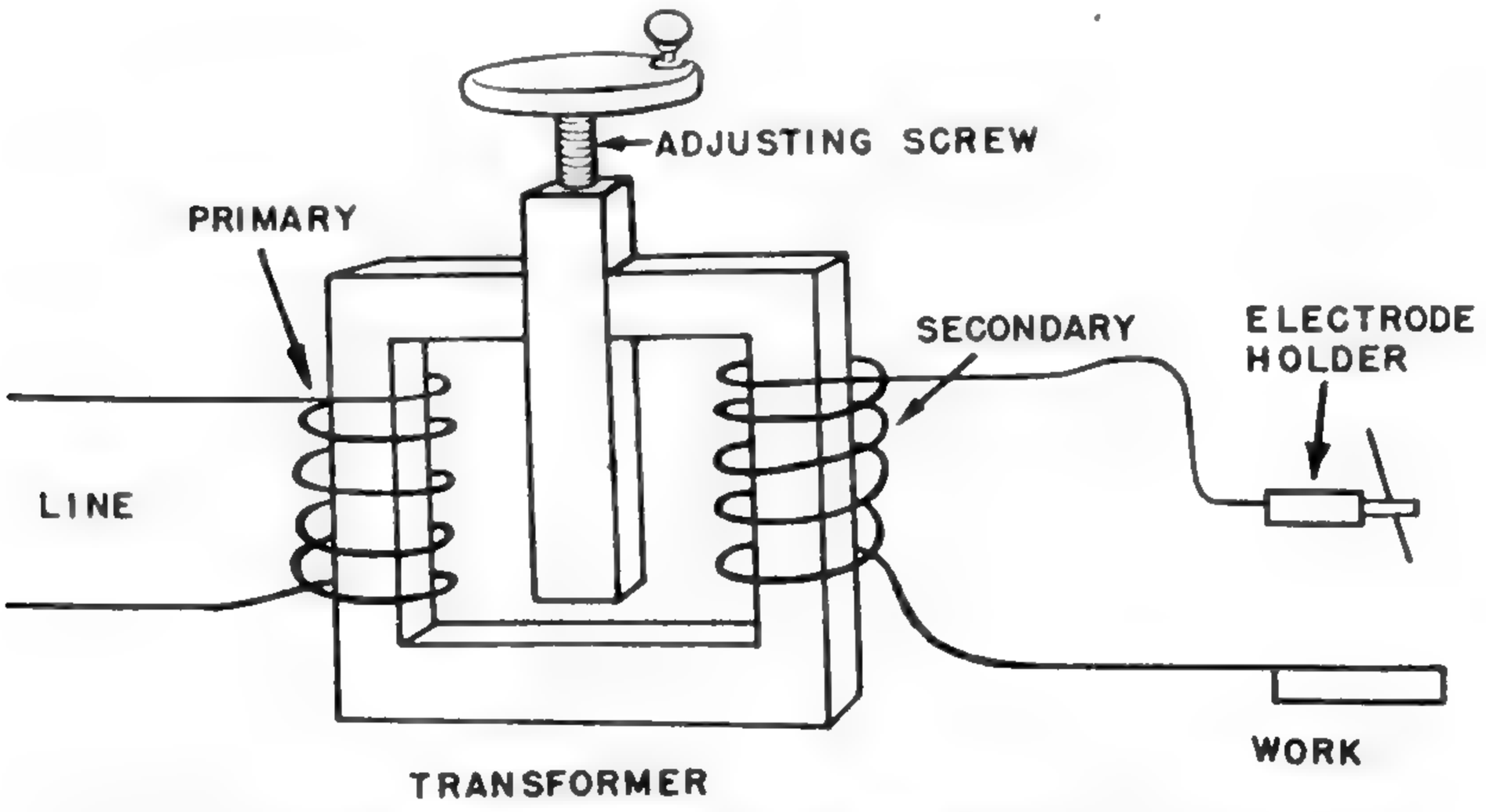

Fig. 7.—Constant Current Transformer with Adjustable Flux Leakage Air Gap

where they enter the welding machine so that they will not be abraded and thus grounded.

The voltage and frequency of the power line should be checked against the information on the nameplate of the welding machine. Many a.c. welding machines have dual voltage terminal boards; care must be taken to use the proper terminals for the voltage of the power line.

The welding machine should be connected to the power system through a fusible safety switch mounted on the wall near the welding machine. Line fuses rated between 150 and 200% of the rated primary line input current of the welding machine should be used. A good safety precaution is to operate all welding machines in one group from the same phase of the power system and with the same polarity to make sure that there is no voltage between the electrode holders of adjacent welding machines.

See Chapter 46 for further information on the safe installation and operation of arc-welding machines.

Maintenance

Manufacturers' instructions with regard to maintenance should be carefully followed. The welder should be on the watch for any evidence of overheating.

Welding machines with screw-type adjustments should have their screws and the bearings on which they run lubricated approximately every six months. Welding machines with chain drives require periodic lubrication at about the same interval.

About twice a year, contactors, switches, relays, and plug and jack connections should be inspected, and contactors cleaned or renewed.

Once a year the primary input current at no load should be measured and checked against the nameplate or instruction book data to make sure that power factor correcting capacitors are functioning. Fan-cooled units should have their fan bearings lubricated at the same time.

DIRECT-CURRENT ARC-WELDING MACHINES

Motor-Driven Single-Operator D.C. Machines

Single-operator, d.c. welding generators are highly specialized designs. Practically all designs are of the self-regulating, variable voltage type. They are made in ratings which have been standardized by the National Electrical Manufacturers Association as shown in Table 3.

150- and 200-amp., 30-volt rated machines are used for light industrial shielded metal-arc welding and inert-gas metal-arc welding as well as general-purpose job-shop work.

200-, 300- and 400-amp., 40-volt rated machines are commonly used for manual and machine welding in industrial plants, and for field erection.

600-amp. rated machines are used, sometimes in pairs, almost exclusively for carbon-arc cutting and submerged-arc welding.

The effect of long welding leads on the loading of a d.c. welding generator should not be overlooked. The resistance of the

Table 3—Ratings for D.C., Motor-Driven, Single-Operator, Welding Machines

Current, Amp.	Load Volts	Duty Cycle, %	Minimum Current at 20 Volt Load |Amp.	Maximum Current at Rated Load Voltage, Amp.[a]	Duty Cycle at Maximum Current and Rated Load Voltage, %[a]
——Rating——			——Welding Current Range——		
1	2	3	4	5	6
150	30	50	20	185	30
200	30	50	30	250	30
200	40	60	40	250	35
300	40	60	60	375	35
400	40	60	80	500	35
600	40	60	120	750	35

[a] Welding machines may be operated at the current shown in Column 5 and duty cycle shown in Column 6 at rated-load volts with approximately the same temperature rises as those specified for the rated amp. and duty cycle (Columns 1 and 3).

NOTES: (1) Load voltage is the voltage between the welding terminals of the machine when current is flowing. (2) In arc welding, duty cycle is defined as the ratio of arc time to total time. For the purpose of standard rating the time period of one complete test cycle is 10 minutes. For example, in the case of a 60% duty cycle, load is applied continuously for 6 min. and shut off for 4 minutes. Load must not be applied for more than 6 min. out of any 10-min. period.

cables and connections cause a voltage drop which is added to the voltage of the arc. This requires more power to be delivered from the motor driving the generator and in case of excessive lead resistance may result in overloading the motor, as well as in reducing the maximum current output of which the machine is capable.

Parallel Operations.—Single-operator, d.c. welding machines may be readily paralleled to produce high values of welding current. The method of connection for parallel operation depends on whether the machines are separately excited or self-excited.

With machines having separate exciters, the two work-lead terminals should be connected together, and the electrode terminals connected together through a switch. The two units should be started with the switch open. Both should be adjusted for the same polarity and the same no-load voltage before the paralleling switch is closed. This may be checked by connecting a voltmeter across the terminals of the paralleling switch (see Fig. 2). The voltmeter should read approximately zero before the paralleling switch is closed.

Welding machines which do not have separate exciters should have, in addition to the paralleling connections described above, an equalizer connection of No. 14 or larger wire. The equalizer is connected from the excitation brush holder of one generator to the corresponding brush holder of the other generator.

Special instructions furnished by the manufacturer should be followed in paralleling welding machines. The current adjustments of machines in parallel should be similar, so that each will produce its own share of the total current.

Power Supply.—Single-operator, d.c. welding machines are obtainable with driving motors of several voltage and frequency ratings. Motor-generator welding machines are usually single units with the motor and generator assembled on the same shaft.

Induction-motor-driven welding machines are available for 220, 440 and 550 volts, 2 phase or 3 phase, 60-, 50- or 25-cycle power supply. Few are made with single-phase motors since a.c. welding machines usually fill the need for single-phase apparatus.

Direct-current, motor-driven welding machines are made with motors wound for 115, 230, 440 and 550 volts. Motors suitable for operation on the widely varying voltage of trolley circuits are also available.

The most common driver is the 220/440, 3-phase, 60-cycle induction motor. Figure 8 shows the characteristic volt-ampere curves of such a welding machine as well as curves for overall machine efficiency, power factor, and current input. A combination of shunt field rheostat control and series field tapping gives a large number of possible drooping volt-ampere characteristics.

The motors of d.c. welding machines usually have a good power factor when under load, and from 30 to 40% lagging power factor at no load. No-load power input ranges between 2 and 5 kw., depending on the rating of the set. The power factor of induction motor-driven welding machines may be improved by the use of static capacitors similar to those used on a.c. welding machines. Some welding machines have been built with synchronous motor drives in order to avoid low, lagging power factors. The use of a synchronous motor provides such a leading power factor as to correct for the lagging power factor.

Control Devices.—One method of compensating for the relatively high no-load input and low no-load power factor of induction-motor-driven welding machines is to equip each set with a shut-down device. This automatic control system disconnects the motor from the power line at a predetermined time after the welder stops welding. The equipment then draws no power from the line until the welder touches his electrode to the work. The motor then starts and continues to run until the predetermined idling interval has been exceeded. The interval is usually made long enough to permit the welder to change electrodes before the set shuts down, in order to elimate unnecessary starting and stopping.

When a shut-down device is used, care must be taken to see that the welding machine does not overheat. Frequent starting, with limited running time, increases the heating of the motor, and both the motor and generator have only limited ventilation between loading periods, since the machine is standing still. Commutator conditions should be checked to make sure that they are not adversely

affected by the elimination of no-load operation.

Devices which give remote control of the welding current are sometimes used. Good practice frequently requires that a different current be used for welding in the overhead, vertical and flat positions, and for different thicknesses of metal. When the welder is welding at a distance from the welding machine, a remote-control device has considerable usefulness.

One simple method involves removing from the welding machine the rheostat used to adjust the welding current and carrying it to the welding position. A cable about the size of a lamp cord is used to connect the rheostat to the welding machine and this permits the welder to adjust the welding current over a limited range without returning to the welding machine.

Another remote control scheme requires a motor to operate the rheostat of the welding machine. The operator is given a push button which is wired to the motor to allow raising and lowering the rheostat setting from the welding position.

Several devices have been developed to operate through the welding cables themselves with no extra conductors. Some of these devices are operated by means of notching relays and require the welder to touch the electrode to the work repeatedly in predetermined code sequences in order to raise or lower the current a little.

Principles of Operation.—The characteristics required of a welding generator are determined by the characteristics of the welding arc. As shown in Fig. 9, the arc has an almost constant voltage, for a given length, regardless of the current in it. The voltage decreases only very slightly with increasing current. Each curve in Fig. 9 represents an approximately constant arc length.

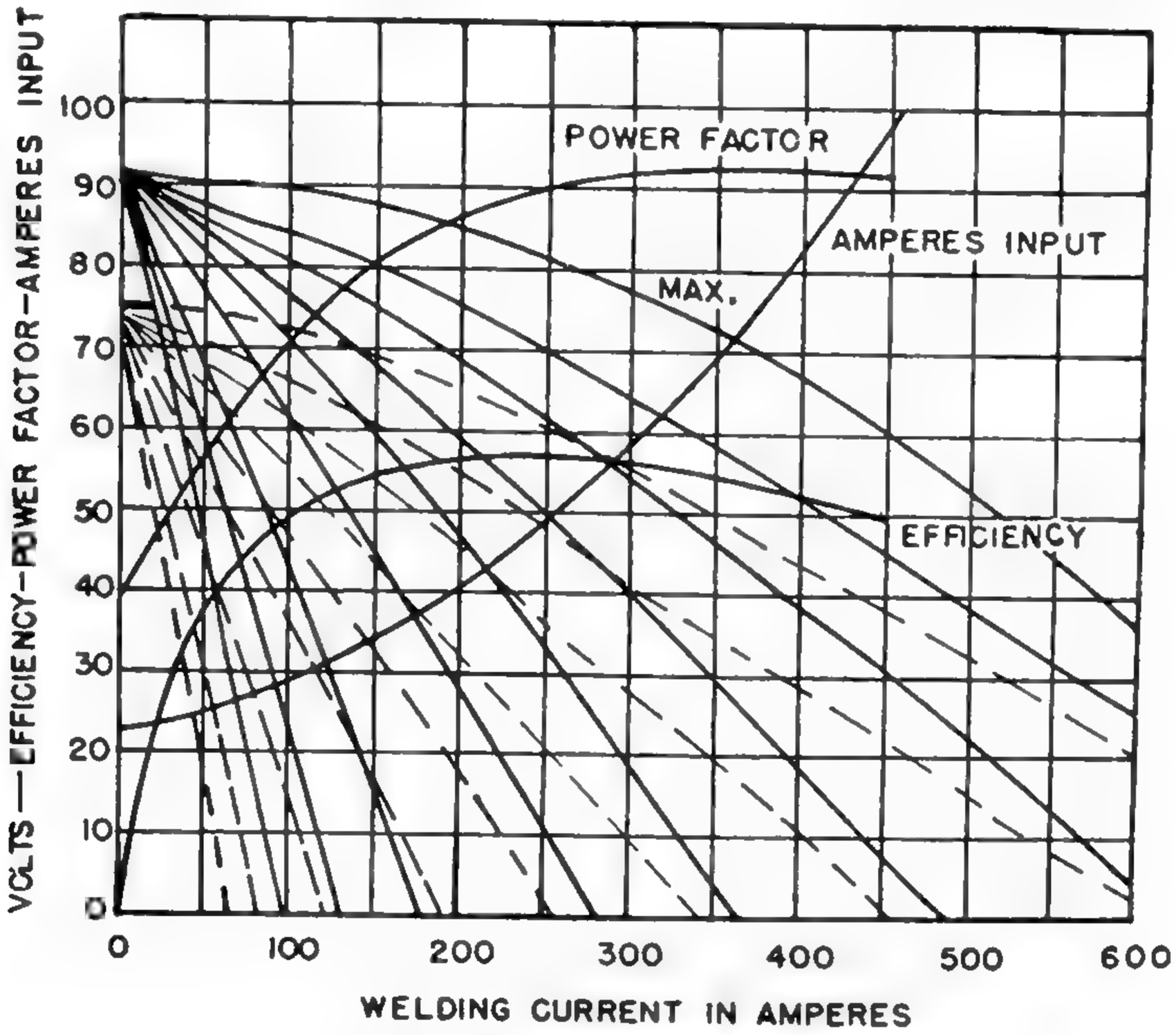

Fig. 8.—Typical Characteristic Curves of Single Operator, D.C. Motor-Generator Welding Machine

In metal-arc welding, the arc voltage varies almost directly with the length of the arc, but reaches a minimun of about 12 volts when the electrode is just about to touch the work. This minimum voltage is assumed to be the sum of the anode and cathode voltage drops of the iron arc.

In order to achieve stability of the generator-and-arc circuit, it is desirable that the volt-ampere characteristic curve of the generator intersect that of the arc at approximately right angles.

Lines *A*. *B*. *C* and *D* on Fig. 10 show

typical volt-ampere characteristics of some welding generators, all adjusted to intersect the arc curve at the same point. Each of these curves is only one of a large number which can be produced by each generator. The generator which produced Curve *C* can be adjusted to have hundreds of other characteristics curves (see Fig. 8) in order to cover its wide range of current adjustment.

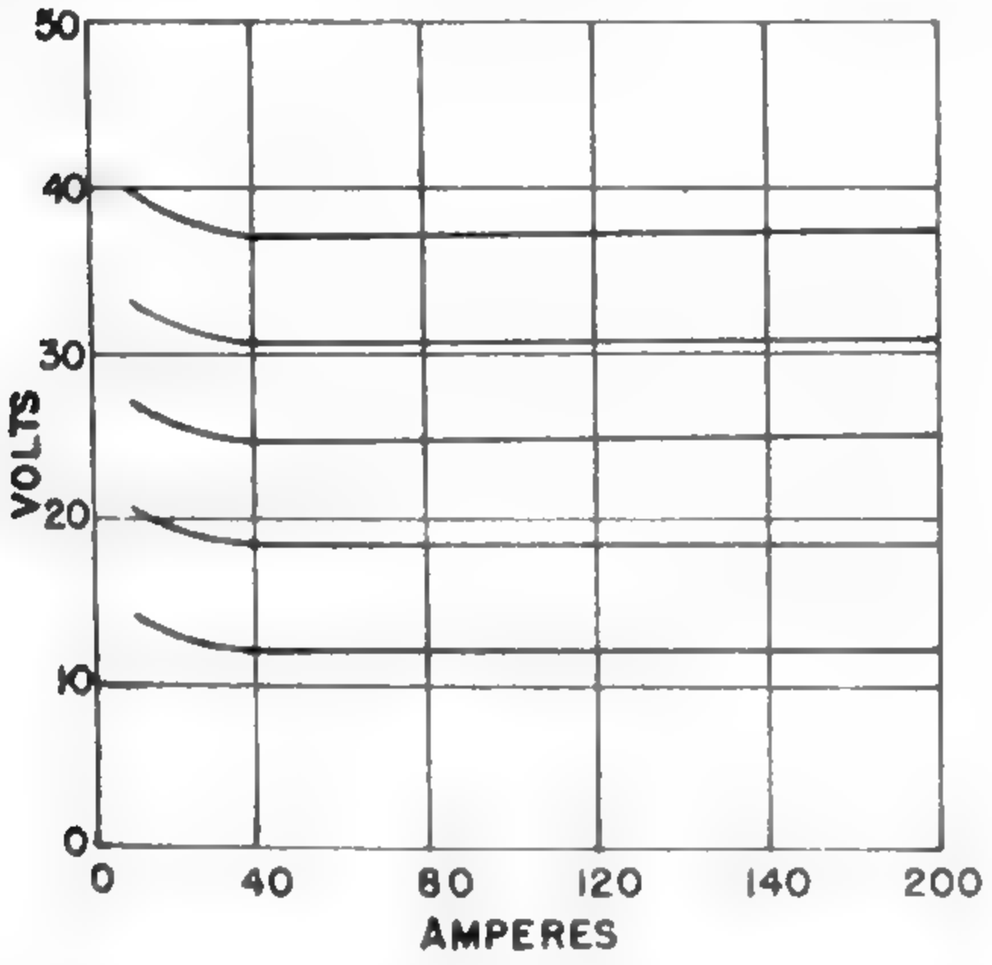

Fig. 9.—Volt-Ampere Curves of Arcs of Various Lengths

Direct-current arc-welding generators have been developed in a large number of designs, depending on the means used to adjust the welding current. One of the earliest, and still widely used, designs employs a generator with separate excitation and differential compounding. The circuit for such a generator is shown in Fig. 11. Later designs of this type eliminate the need for a stabilizer or external reactor, by reactance built into the generator. In order to achieve a wide range of welding current, adjustment of the differential series field is usually provided, sometimes by means of an adjustable shunt across the series field and sometimes by tapping its windings.

A design shown schematically in Fig. 12 arranges the generator so that one-half its armature winding opposes the other half when loaded and thus produces the approximately constant current characteristics desired. This welding generator obtains its excitation from a third brush located so as to utilize the constant component of armature voltage produced by the main field poles. Drooping characteristic at the generator terminals results from variable voltage component produced by a variable cross-pole field. This design may also have tapped series fields in order to provide a wide range of current adjustment.

Other types of generators use different methods of adjusting the welding current and providing excitation. Some move an iron block with respect to the main field poles to adjust the leakage flux around the armature to vary the welding current. Others shift the brushes around the commutator to adjust the output current by varying the effective armature reaction. Most such designs have secondary adjustment by variation of the field excitation.

In addition to the requirements as to the shape of the volt-ampere characteristic and the range of output current adjustment, the welding arc requires rapid response of the generator voltage. The arc voltage varies widely and extremely rapidly during normal welding, as well as during intermittent short-circuiting. If the arc is to be maintained, the generator voltage must adjust itself correspondingly.

Excessive changes in the instantaneous flow of welding current during the rapid

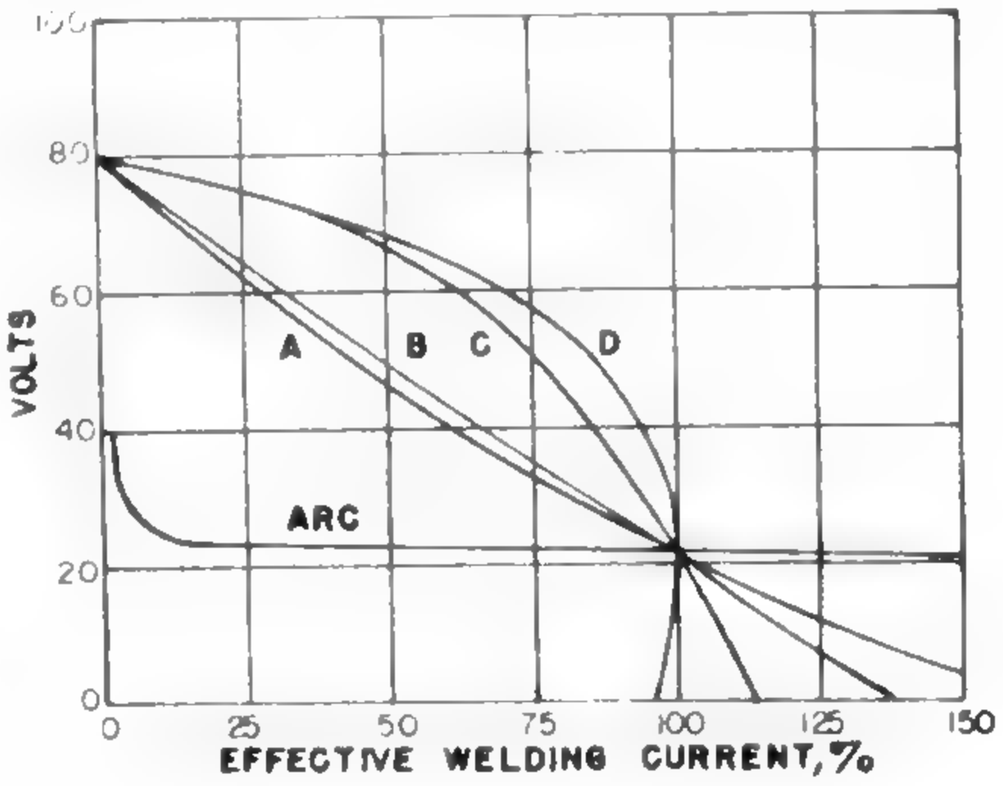

Fig. 10.—Volt-Ampere Characteristic Curves of Four Generators Adjusted to Intersect at Same Point of Arc Curve

changes in arc voltage cannot be tolerated. A large increase in current in the arc during intervals of low arc voltage will result in increased spatter of the weld metal. Conversely, a large decrease in the arc current results in instability which may extinguish the arc.

The welding performace of generators is usually evaluated by means of oscillographic tests. The oscillogram is a visual record of the changes in welding current

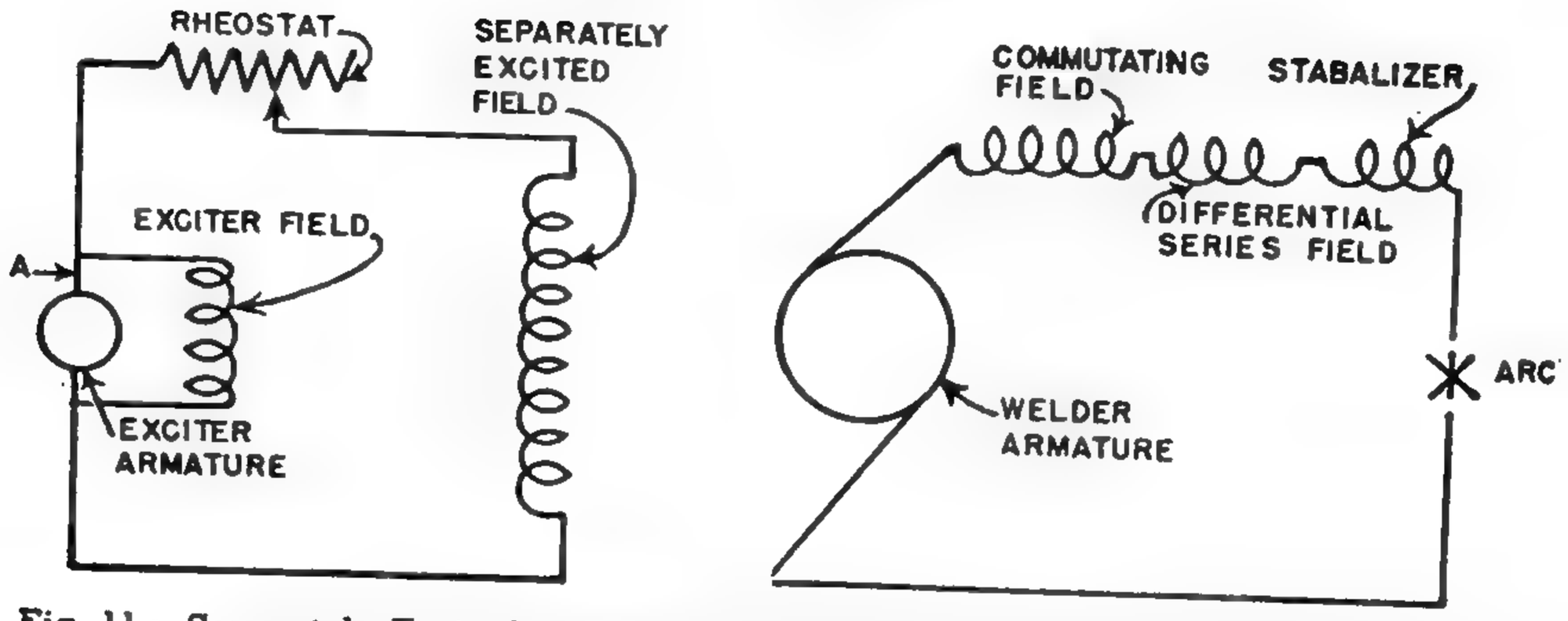

Fig. 11.—Separately-Excited, Differentially-Compounded Welding Generator Circuit

and generator voltage during predetermined changes in the arc voltage. When the generator is short-circuited from no load, as in establishing an arc, the oscillogram should show that the current does not rise to an excessive peak value. Similar tests show current surges when the generator is short-circuited while carrying normal load, and voltage recovery when a short-circuit is suddenly broken. The United States Navy Specifications have been generally used as standards for such tests.

Installation.—Installations of welding machines should meet applicable requirements of the *National Electrical Code* and local codes. Welding machines should be located in a clean, dry place, and should be kept off dirt floors. When used outdoors, suitable protection from the weather should always be provided, with care taken to assure against restriction of the ventilating air.

Welding machines located where there is much dust in the air, and particularly those subjected to dust from paint spray-

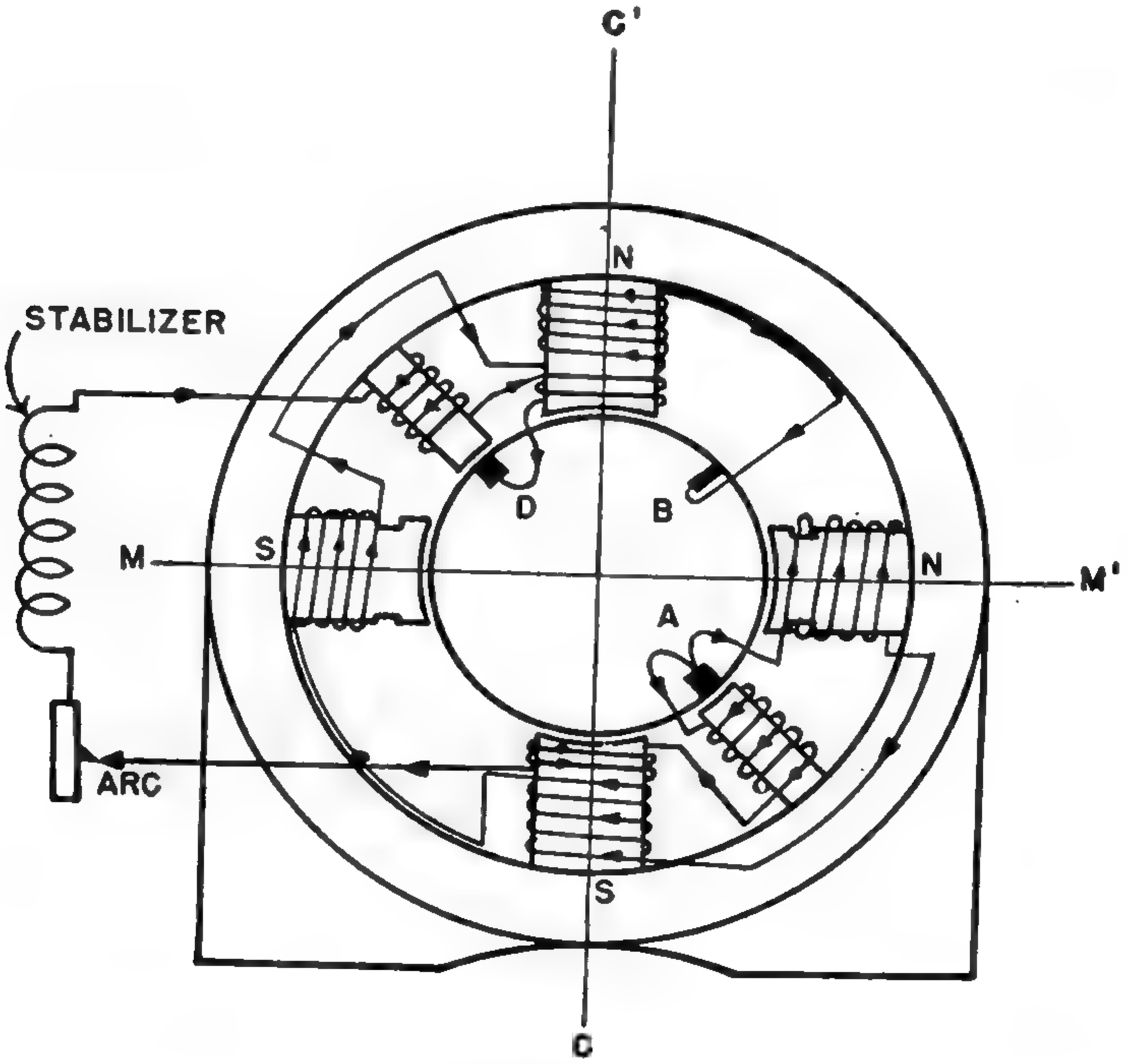

Fig. 12.—Type of Self-ExciteWelding Generator

ing, may be equipped with air filters. Care must be taken to prevent restriction of the ventilating air by permitting filters to become plugged or by using filters too small for the air requirements of the machine.

Power line leads should be neatly attached, making sure that no strands touch other current-carrying parts or the frame of the machine. Each welding machine should be carefully grounded by a grounding conductor securely attached to the frame.

Welding machines should not be located under work benches or in enclosures unless an adequate supply of cooling air is available and recirculation of ventilating air is prevented.

The voltage, frequency and phases of the power supply should be checked against those shown on the nameplate of the machine. If it is connectable for either of two voltages, it should be checked to see that it is connected for the proper voltage.

Maintenance.—Manufacturers' instructions regarding the maintenance of welding machines should be carefully carried out. About once every three months a welding machine should be checked over and the dust blown out, using clean, dry compressed air at 25 to 30 psi. pressure. Once a year, the contacts of the motor starter switches and rheostat should be inspected, cleaned or replaced as necessary. Brushes should be inspected frequently to make sure that they are not too short to bear properly on the commutator. When new brushes are required, they should be of the same grade as originally used. All brush holders should be checked to see that the fingers are free and that brushes move freely in their holders.

If the commutator is burned or rough, it should be cleaned with sand paper or a commutator stone, or the armature should be removed and the commutator turned on a lathe if necessary.

About twice a year the bearings should be inspected. If there is ample grease in the bearings, and it does not have a sour smell, it may be run until the next inspection. When new grease is added, all old grease should be first cleaned out of the bearing housing. Bearing housings should be filled only to about one-half full.

See Chapter 46 for further information on the safe installation and operation of arc-welding machines.

Engine-Driven, Single-Operator, D.C. Welding Machines

Engine-driven welding machines employ the same type of generators as are used on electric motor-driven welding machines. Both gasoline and Diesel engines are widely used where there is no electric power supply. Ratings are the same as those shown in Table 3.

Similar generators are built with neither motor nor engine, but with a shaft extension for belt or direct connection to any suitable source of power.

Engines for arc-welding machines should be selected with care and with consideration for the overload capacity inherent in welding machine design. For example, a 300-amp. welding machine has a rated output of 12 kw. Taking account of the efficiency of the generator, about 21 hp. will be required to drive the generator. Since the generator is rated at 60% duty cycle and 50°C. temperature rise, an electric motor rated at only 15 hp. continuous with 40°C. temperature rise could drive the generator satisfactorily.

The engine is, however, usually rated at its maximum possible output. General practice is to publish horsepower ratings which include the power required by the fan, water pump and other engine accessories. This accessory load reduces the power available at the engine shaft. For example a 21-hp. engine may have an engine accessory load of 5 hp., leaving an available output of 16 hp.

In order to provide for engine accessory load, generator losses and the overcurrent capacity of the generator, a good rule of thumb is to use about 70 cu. in. of piston displacement per 100 amp. of generator rating. This is based on an engine speed of between 1500 and 2000 rpm.

Figure 13 shows the fuel consumption curves of three sizes of typical engine-driven welding machines under continuous load at 40 volts.

Control Devices.—Most engine-driven welding machines are equipped with automatic idling devices to slow the engine down to a lower speed during non-welding periods. The fuel consumption of the engine running at no-load will be reduced roughly in proportion to the reduction in speed. The no-load fuel consumption of a

typical 300-amp. gasoline-engine-driven welding machine is 1.6 gal. per hr., and of a 300-amp. Diesel-engine-driven unit about 0.9 gal. of oil per hr. at full speed.

The net saving of fuel in the gasoline-engine-driven welding machine is less than that indicated by the figures above due to the fact that the acceleration pump on the carburetor feeds a gush of gasoline to the engine each time it is accelerated. Fuel thus introduced is not burned as efficiently as with normal fuel-air ratios.

Care should be taken not to operate engine-driven welding machines at too low an idling speed, particularly in hot weather, since the cooling afforded by the fan and radiator will be drastically reduced at low engine speeds.

Some engine-driven welding machines are equipped with overspeed devices which open the ignition circuit if the engine exceeds the rated speed of the generator by 15 to 20%.

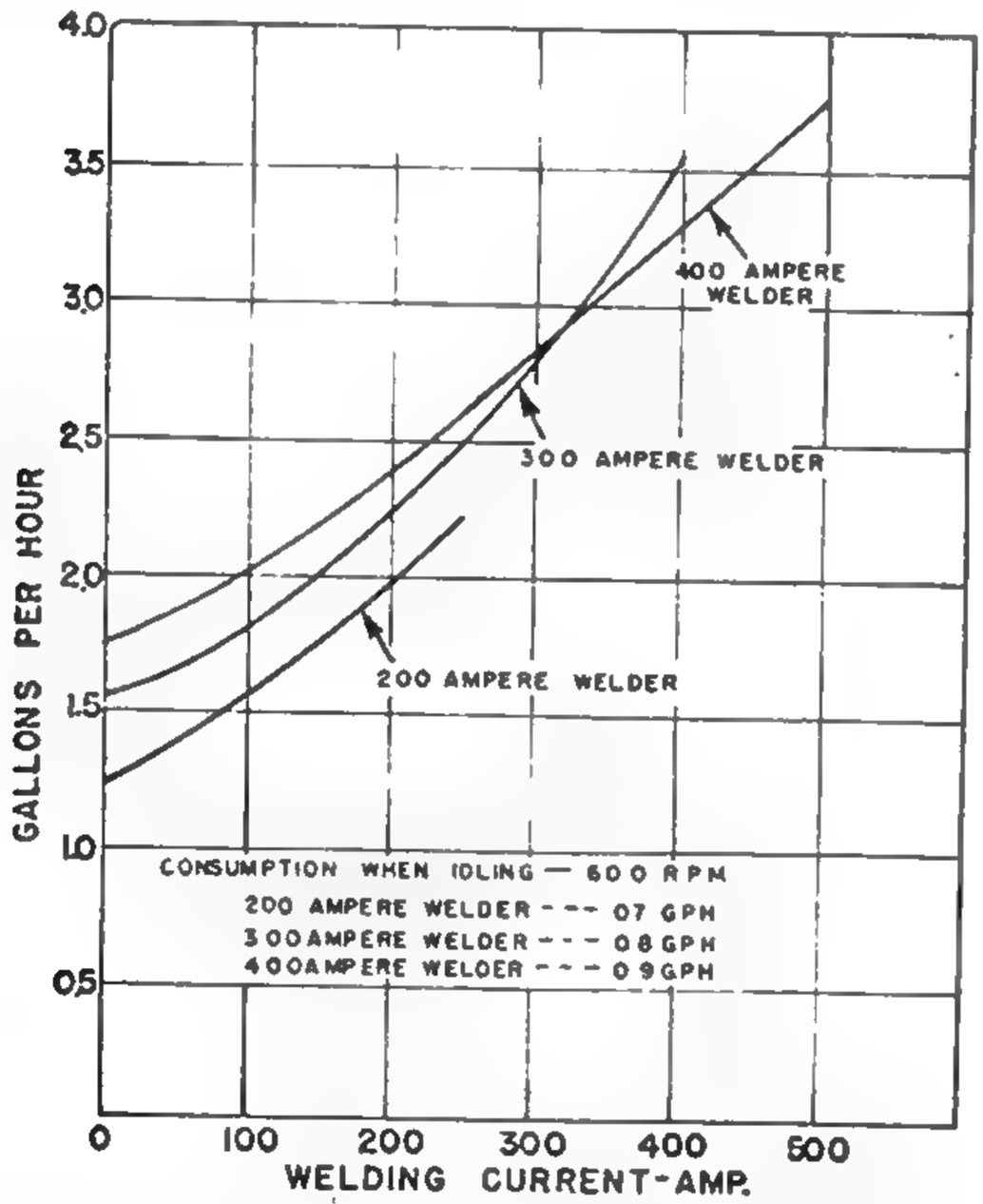

Fig. 13.—Fuel Consumption Curves for Gasoline-Engine-Driven Welding Generators

Rectifier Type, Single-Operator, D.C. Welding Machines

Direct-current arc-welding machines have been designed without any moving parts. Usually they consist of a transformer to change the power supply voltage to the proper voltage, a reactor for adjustment of the current, a rectifier to change the alternating current to direct current, and sometimes another reactor to reduce the ripple in the output current.

Dry plate rectifiers may have either copper oxide or selenium plates. Such units are more costly to build than either motor-generator d.c. welding machines or transformer a.c. welding machines. With few exceptions, they have been made only for current ratings not included in standard lines of a.c. and d.c. welding machines.

Several types of electronic tubes may be used as rectifiers for welding service, although they do not have the durability of other types of welding machines. They are usually used in groups of six as polyphase rectifiers, and when so used, do not require a ripple-eliminating reactor. Such equipment has been used for very low current welding as required for thin gages of special alloy steels.

Multiple-Operator D.C. Equipment

Where there is a concentration of welders in a small area, such as is frequently encountered in shipbuilding, multiple-operator equipment has proved economical as regards cost of installation and operation.

Assume a certain small area in which there are 100 welders, each operating at 200 amp. per arc about 25% of the time. Where single-operator units are employed usual practice is to install a 200- or 300-amp. single-operator welding machine for each welder so that a total installed welding capacity of 20,000 or 30,000 amp. is required. With a multiple-operator system, however, 5000 amp. in generating capacity will handle the load. This is because each welder welding at 200 amp. requires this current for only one-quarter of the time so that each welder's average load is 50 amperes.

Generating capacity is generally installed as large 1000-, 1500- or 2000-amp., 60- or 70-volt generators. Large copper busses are run from the generator to the welding centers and there connected to welding outlet panels. Sometimes individual panels are installed for each welder; sometimes as many as 10 circuits may be grouped in one panel. Each circuit is basically a resistor connected in series with the electrode holder. The resistor is adjustable so that the amount of welding current it passes can be controlled.

In large installations, multiple-operator equipment will usually result in reduced fixed cost of equipment and cable, reduc-

tion in the amount of power used and a large reduction in maintenance. The individual resistor panels can usually be located close to the welder so that it is convenient for him to make current adjustments. It should be observed that with a multiple-operator, d.c. installation, all welders must weld with the same polarity, since individual circuits cannot conveniently be reversed.

Capacity.—Multiple-operator generators are built in standard ratings of 600, 750, 1000, 1500, 2000 and 2500 amperes. They may be provided with motors for any combination of voltage, frequency and phases. Synchronous or induction motors are used, sometimes wound for 2300 volts.

The average welder actually welds only a small percentage of the time. It is nearly always below 25%. For this reason, it is common practice to install multiple-operator welding equipments with a generator capacity of 30 to 50 amp. per arc, although the individual resistor panels may have ratings up to 300 or 400 amp. each. As many as 300 or 400 arcs have been connected to one group of generators, connected in parallel.

Parallel Operation.—Groups of constant potential generators may readily be paralleled for use on multiple-operator welding systems, if they are properly connected with an equalizer. The individual generator control panels should include reverse current relays. Overspeed relays have sometimes been used for additional protection against motoring of the generators.

Principle of Operation.—The multiple-operator system employs a constant voltage power source with a resistor in series with the arc, to regulate the current. In order to make the arc stable, the voltage of the constant potential source must be higher than the arc voltage. The resistor absorbs the difference in voltage.

The current which will flow in the circuit is limited to that value which produces a voltage drop in the resistor equal to the difference between the constant potential source voltage and the arc voltage. Varying the value of the resistance will change the value of current required to produce this drop and thus give control of the welding current.

For information on shielded metal-arc welding see Chapter 10

B. INERT-GAS METAL-ARC WELDING EQUIPMENT

Inert-gas metal-arc welding, utilizing a semi-permanent electrode such as tungsten or carbon, requires special electrode holders and a source of welding power, in addition to the gas supply and regulating equipment. Both a.c. and d.c. are used. Alternating current requires special features to assure adequate arc stability; direct current involves no special requirements of the welding power supply.

Practically all inert-gas metal-arc welding machines may be used, with suitable electrode holders, as power supply units for shielded metal-arc welding.

ALTERNATING-CURRENT WELDING MACHINES

Alternating-current inert-gas metal-arc welding is done with three general classifications of equipment:

1. Specially designed *balanced wave* units producing no direct current component and requiring no radio frequency energy for arc stabilization.
2. Specially rated units with simple circuits involving radio frequency stabilization of the arc
3. Ordinary shielded metal-arc a.c. welding machines with external radio frequency oscillators for arc stabilization.

Inert-gas metal arc welding machines utilizing radio frequency energy for arc stabilization are subject to the Rules of the Federal Communications Commission

Balanced Wave Welding Machines

Inert-gas metal-arc welding machines of the fully balanced wave type have been built with characteristics as shown in Table 4.

Equipment of this type is usually used with argon gas but may be used with high purity helium in the welding of aluminum and magnesium. It may also be used for welding other metals.

Welding machines which have been type approved by the Federal Communications Commission have been built in ratings of 150, 200, 300, 400, 500 and 750 amperes. Such equipment employs radio frequency oscillators operating within frequency bands assigned by the FCC, and may re-

Table 4—Ratings for A.C. Balanced Wave Inert-Gas Metal-Arc Welding Machines

Rated Current, Amp.	Range of Current Adjustment—High Range, Amp.	Range of Current Adjustment—Low Range, Amp.	Rated Duty Cycle, %	Full Load Input, Kva.
200	40–200	30–120	60	14
400	90–400	60–250	60	28
800	175–800	125–500	Continuous	64

quire the use of special electrode holders and cables with electrical characteristics tuned to prevent the emission of excessive radiation on off-band frequencies.

Machines employing off-band oscillators have been built in large numbers in standard NEMA sizes shown in Table 1. Such units do not have type approval of the FCC and may require special methods of filtering, shielding and grounding of their primary and secondary circuits in order to prevent harmful interference with established radio services.

While such units are built in standard NEMA sizes, their ratings, input current and other electrical characteristics are quite different from those encountered in metal-arc welding, because of the magnetic saturation of their cores by the direct current which flows in their secondary circuits. This causes unusally high input currents which may produce excessive heating and these welding machines are specially designed to take care of this extra primary input.

Standard Shielded Metal-Arc A.C. Welding Machines

Ordinary shielded metal-arc a.c. welding machines may be used with separate radio frequency arc stabilization oscillators. In such installations, cognizance must be taken of the extra heating due to the d.c. component in the arc, as mentioned above, and particular care must be taken to prevent harmful radio interference, since the oscillator must be arranged to operate continuously.

It should be noted that ordinary alternating current ammeters employing current transformers, and *hook-on* ammeters operating on the current transformer principle, will not give reliable readings of total current in a.c. circuits carrying a d.c. component. For this reason, when accurate measurement of the output current of such welding machines is required, direct reading ammeters which carry the full current through the instrument itself should be employed.

Capacity

Since a.c. inert-gas metal-arc welding machines are usually applied primarily to the welding of aluminum, it is convenient to express their work capacity in terms of this metal. However, other metals will require similar current levels.

In the selection of welding machine sizes, a rule of thumb is to estimate the welding current required as 25 amp. plus 1 amp. per 0.001 in. of metal thickness. For example, welding $^{5}/_{32}$-in. thick aluminum will require roughly 25 plus 156 amp. or 181 amperes. A 200-amp. machine would handle the work successfully.

Power Supply

Industrial welding machines are built for 220, 380, 440 or 550 volt power circuits. Power factor correcting capacitors are usually built into the welding machine, although power factors may run considerably lower than those common in shielded metal-arc a.c. welding machines. This is due to the fact that arc voltages in the inert-gas process are lower than in the shielded metal-arc and thus require a higher reactive voltage drop in the welding machine to limit the welding current to the desired value. In addition, many inert-gas welding machines employ higher-than-normal voltage secondary windings which increases the requirement for reactive voltage drop. In units not having direct current preventing means, the input power factor may be still further reduced by the excessive magnetizing currents required for saturated cores.

The input kva. to inert-gas welding machines is usually higher than to shielded metal-arc welding machines of comparable output by reason of the low power factor just mentioned. For example, at 300-amp. output, a shielded metal-arc welding machine might have an input of 13.8 kva. At the same current, an inert-gas welding machine operating with argon on aluminum may have an input of 19 to 25 kva., depending on its design.

Special Requirements

The special requirements for inert-gas metal-arc a.c. welding machines are the result of the tendency of the inert-gas metal arc to rectify alternating current. In the arc between tungsten and aluminum in argon, for example, the tungsten is a much better electron emitter than aluminum and therefore the arc voltage during the tungsten emission half cycle is much lower than that during the aluminum emission half cycle. This results not only in a tendency for the arc to be extinguished, but in the flow of a direct current through the welding arc and its power supply by reason of the unbalanced arc voltages. Unless this flow of direct current is prevented, partial, or frequently even complete, rectification of the alternating current into direct current results. Where complete rectification occurs, the resulting unidirectional pulsating current is in such a direction that it does not produce a clean bead and coalescence of the molten metal. Even when rectification is incomplete, i.e., where there is a direct current component with more current flowing in one direction than the other, several undesirable results occur. The core of the welding machine may be oversaturated with consequent excessive current input; penetration of the molten pool into the base metal is less than with the equivalent balanced wave alternating current.

Several methods have been devised to minimize or eliminate the rectification and instability characteristics of the inert-gas welding arc. The arc may be prevented from going out by superimposing on the normal 60-cycle voltage of the welding machine radio frequency energy which serves to keep the arc gap ionized and thus to keep the arc alive. This action assists the establishment of the arc in the aluminum-emission half cycle, and helps to more nearly balance the currents in the two directions.

The arc may be stabilized by the use of normal frequency induced voltages sufficiently high to prevent complete rectification, by the use of auxiliary secondary oscillating circuits with a natural frequency of a few thousand cycles per second, or by a combination of these characteristics. The extra induced voltage is provided by secondary windings having a no-load voltage higher than is normal in a.c. metal-arc welding machines. Voltage-reducing control panels may be incorporated to keep open-circuit idling voltages low.

Even partial rectification can be completely eliminated by the use of series capacitors which prevent the passage of any direct current, while allowing free passage of alternating current through the arc circuit. Other means of balancing the alternating current have been employed or proposed, including the use of storage batteries in series with the arc, rectifier circuits of unbalanced characteristics in series with the arc, and so-called filter circuits in which a high-reactance, low-resistance path for direct current is placed in parallel with the secondary winding of the welding machine.

High Frequency Pilots

Radio frequency current is often applied to the electrode in inert-gas metal-arc welding. There are two reasons for doing this: First, it facilitates striking the arc with or without contact of the electrode on the work; second, it helps to stabilize the arc as discussed under special requirements above, when the circuit used lacks inherent arc stability. Until the middle of 1949, the radio frequency oscillators used to supply this energy in commercial welding machines have been of the spark gap type. These units may be built into the welding machine enclosure or mounted separately. In any case, the radio frequency energy is transferred from the spark gap circuit to the welding circuit by means of an air core transformer whose secondary is in series with the arc circuit and carries the full welding current. The usual form of oscillator is shown in the diagram in Fig. 14. It consists of a small transformer which produces a voltage of several thousand volts, connected in series with a spark gap of from 0.005 to 0.015 in. length (frequently two or more such gaps are used in series) and an inductance which forms the primary of the air core transformer referred to previously. A capacitor is connected across the secondary of the high-voltage transformer. Energy from the high-voltage transformer charges the capacitor rapidly, raising its voltage to a value sufficiently high to break down the gap. An oscillatory discharge current is thus produced, which passes through the primary of the air core transformer and induces the pilot voltage in its

secondary. The frequency of the oscillations is usually arranged to fall between 200,000 and 2,000,000 cycles per second. Oscillations are quickly damped and restarted as soon as the capacitor voltage builds up again. The result is a series of closely spaced bursts of energy at radio frequencies which produce voltages of sufficiently high value at the electrode to break down the gap between the electrode and the work. This creates a path for the normal frequency or direct current supplied to the resulting arc by the welding current supply circuit.

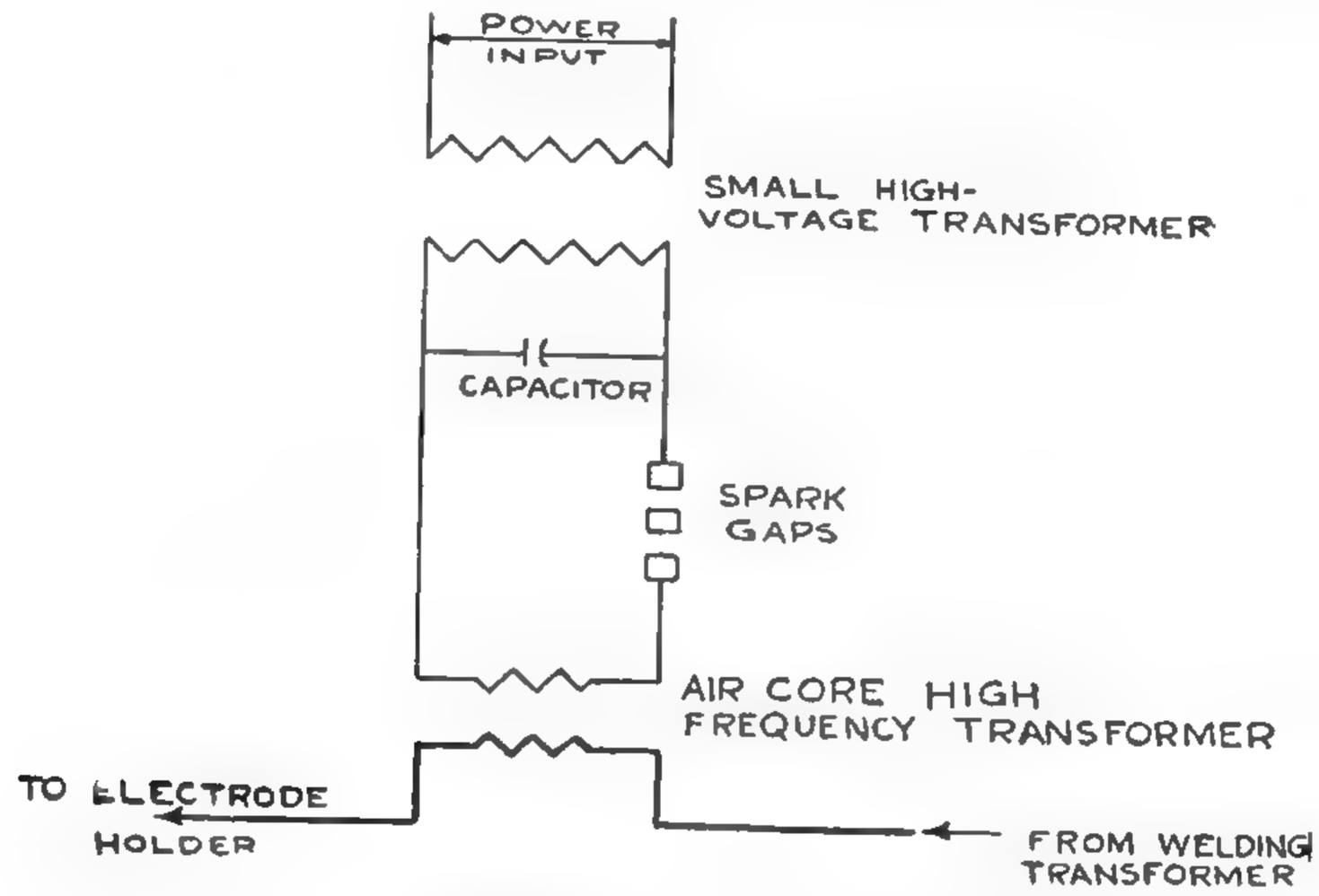

Fig. 14.—High-Frequency Oscillator

While ordinarily such high voltages would be dangerous, at radio frequencies they are harmless. Sparks will produce a feeling of pricking or burning, but since the skin effect characteristic of radio frequency current flow prevents the current from flowing through the blood stream or any vital organs, it is not hazardous from the point of view of shock. The total energy involved in the discharge is small enough so that severe burning does not occur on short exposure, when damped oscillations are used, since the bursts of energy are separated by sufficient time to keep their heating effect low.

More recently, tube-type oscillators have been developed in order to permit operation on the frequency bands assigned for industrial use by the Federal Communications Commission. The function of these oscillators is the same as that of the spark-gap type, but they do not produce damped oscillations. Whereas the spark-gap type cannot be tuned accurately to any specific frequency, the tube-type oscillators do not have this limitation and can therefore be operated in assigned bands.

In any case, where radio frequency oscillators are used to stabilize the arc, provision must be made to prevent troublesome radio interference. With spark-gap oscillators, this means that filtering, shielding and grounding instructions must be carefully observed. With tube-type oscillators, the frequency must be maintained within the limits of the band, and suitable tuning or filtering means provided by preventing unwanted harmonic radiation.

Control Devices

In addition to the inert-gas metal-arc welding machine itself, various control devices are usually required to make a complete installation. These include gas valves, water valves, power circuit relays and sometimes crater fillers. These devices may be built into the power unit enclosure or they may be mounted separately.

Gas valves are usually solenoid valves controlled by time delay circuits in such a way that the gas flow is not shut off when the welding arc is broken, but at a predetermined time interval after the arc has been broken. The duration of the time delay is usually fixed at a value high enough to provide a gas shield while the welding electrode is cooling down below the temperature at which it oxidizes rapidly. This time delay is usually in the range of 40 to 50 sec. for large electrodes. Some gas-control systems have adjustable time delay so that when small, rapidly

cooling electrodes are used, the gas is shut off sooner. It is desirable to have the control arranged so that the gas flow may be started either automatically or manually before the welding arc is established. This facilitates striking the arc and purges, from the gas passages of the electrode holder, air which would cause oxidation of the electrode and work.

Water valves are not infrequently used to shut off the flow of cooling water through water-cooled electrode holders in order to conserve water and to prevent sweating of the electrode holder in humid weather. Such valves may be solenoid-operated devices controlled by the same relays which control the gas flow valves.

In welding circuits which have sufficient inherent stability to operate successfully without continuous radio frequency energy, additional relay equipment is often used to provide operation of the oscillator only long enough to make it possible to establish the arc without contact of the electrode on the work. These circuits employ very short time-delay intervals so that the oscillator is energized for as little as 0.01 second.

Crater-filling devices are used to reduce the current at the end of a weld to a value low enough to permit finishing off the weld without leaving an appreciable crater. Usually, such features must be built into the welding equipment, since they operate by moving the welding machine's current control mechanism by means of an air cylinder or an electric motor.

DIRECT-CURRENT WELDING MACHINES

The capacity of d.c. welding machines required for inert-gas welding depends on the range of electrode diameters which are to be used. Table 5 shows the range of direct current usable with various tungsten electrode diameters. Generally, a 200- or 300-amp., d.c. arc-welding machine meets the requirements of the average fabricating shop. Where currents below the range of such welding machines are needed, as in welding materials down to a few thousandths of an inch in thickness, low current attachments (series resistors) are used to reduce the minimum current available from the machine.

For welding material over $^{3}/_{8}$-in. thick, particularly copper, much higher currents than are available from 300-amp. welding machines are often used, and machines having larger ratings or several welding machines operated in parallel are used to furnish the welding current.

There are no special requirements for welding sets used in d.c. inert-gas metal-arc welding. Standard d.c. welding machines of sufficient current output range to meet the requirements of the work are almost invariably employed. In some installations, radio frequency pilot circuits are used to permit establishing the arc without contact of the electrode to the work; they are not needed for stabilizing the arc when proper conditions of current level, gas flow and electrode size are maintained.

Where primary electric power supply is not available, engine-driven a.c. welding machines may be used. A unit for such use includes a high frequency device, foot-operated gas valve and a complete water circulating system to cool the electrode holder.

OTHER EQUIPMENT

Manual Electrode Holders

The inert-gas metal-arc electrode holder, or torch, is used to hold the electrode which may be tungsten wire or rod, or a carbon rod. It introduces an envelope of shielding gas around the electrode and conducts electricity into the electrode. In higher current ratings, it is cooled by water circulating in the electrode holder. Figure 15 shows a water-cooled electrode holder, partly sectioned to show its internal construction. Straight, tubular mounting arrangements suitable for machine welding, or a handle for manual welding, may be incorporated in electrode holders of this type.

Air-cooled electrode holders are made in capacities up to approximately 100 amp., and are usually furnished with collets for holding tungsten electrodes of a number of different diameters. The range of tungsten diameters used in air-cooled holders is 0.010, 0.020, 0.040, $^{1}/_{16}$, $^{3}/_{32}$, $^{1}/_{8}$ and $^{5}/_{32}$ inch. This range of electrode sizes permits the use of air-cooled holders for work ranging in thickness from a few thousandths of an inch to approximately $^{1}/_{8}$ inch.

Water-cooled electrode holders have been built in a variety of types and sizes, with ratings ranging from 200 to 800 amperes. Figure 16 shows one design of water-cooled electrode holder, in which a

cylindrical junction box is used to introduce the water lines, a gas line and the electrical conductors into a single hose assembly. Most water-cooled electrode holders are furnished with collets for a number of tungsten diameters. A typical range of collet sizes for a 400-amp. electrode holder is $^1/_{16}$, $^3/_{32}$, $^1/_8$, $^5/_{32}$, $^3/_{16}$, and $^1/_4$ inch.

The capacity of an electrode holder in terms of work thickness is usually determined by the capacity of the tungsten electrodes with which it may be used. Figures on tungsten electrodes capacities are given in Table 5. However, the maximum current which can be handled by an electrode holder, regardless of electrode size, is usually governed by the permissible rise in temperature of the cooling water, and sometimes by the ability of the nozzle to withstand the heating of the arc. Cooling water temperature rises should, in general, be limited to a value which will not cause excessive deposition of scale from the water, which might plug the cooling water passages in the electrode holder.

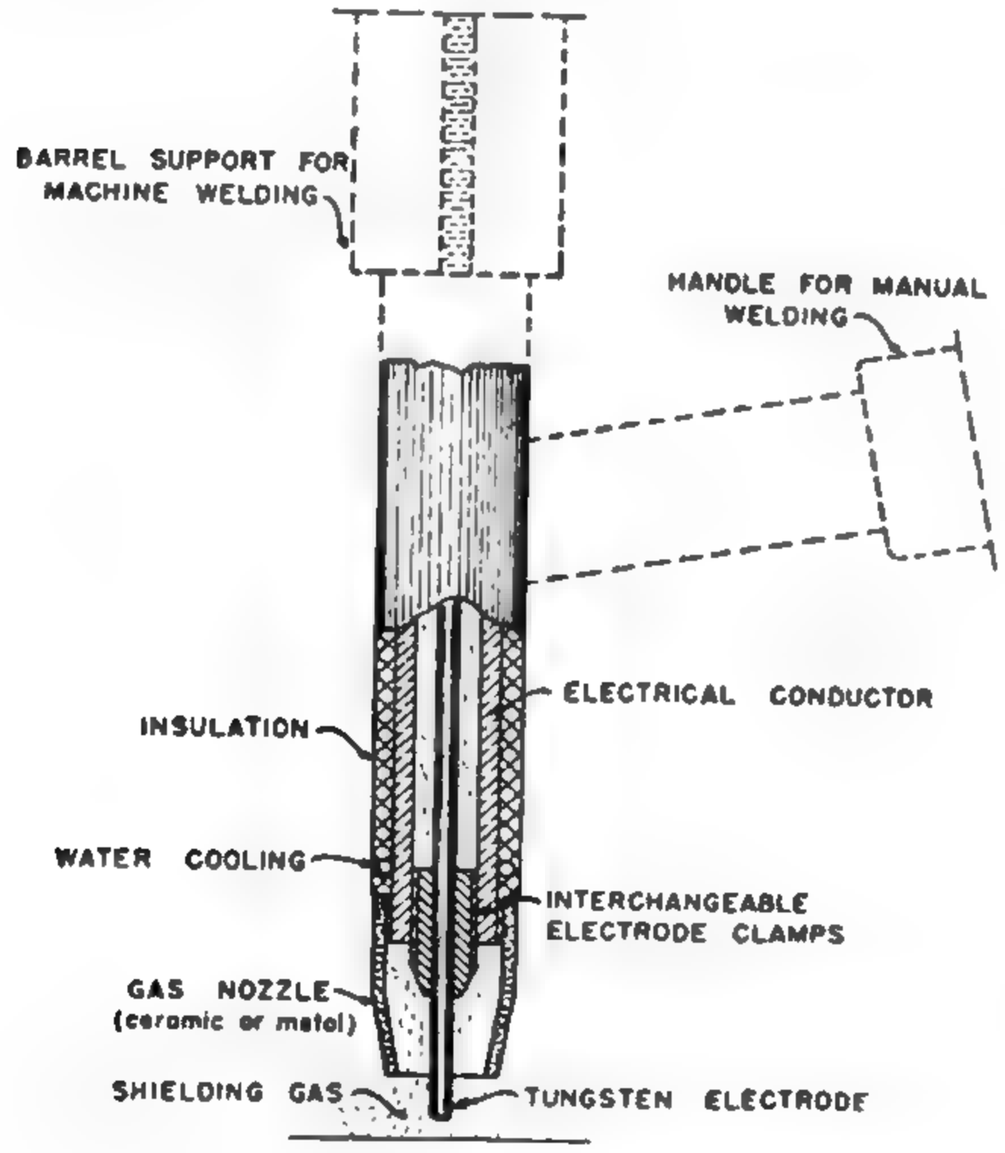

Fig. 15.—Water-Cooled Inert-Gas Metal-Arc Welding Electrode Holder

Construction.—The design of inert-gas metal-arc electrode holders, particularly the water-cooled type, is not as simple as it might appear at first glance. Besides the problem of introducing cooling water into parts that will give adequate cooling for the electrode clamps and the gas nozzles, the major objectives are to keep the visibility of the molten pool good, to keep the weight of the electrode holder to a minimum, to introduce the current into the electrode without excessive localized heating and to provide adequate gas shielding of the arc with a minimum of gas consumption.

Other design considerations include insulation to protect the welder from high frequency pilot voltages and to prevent

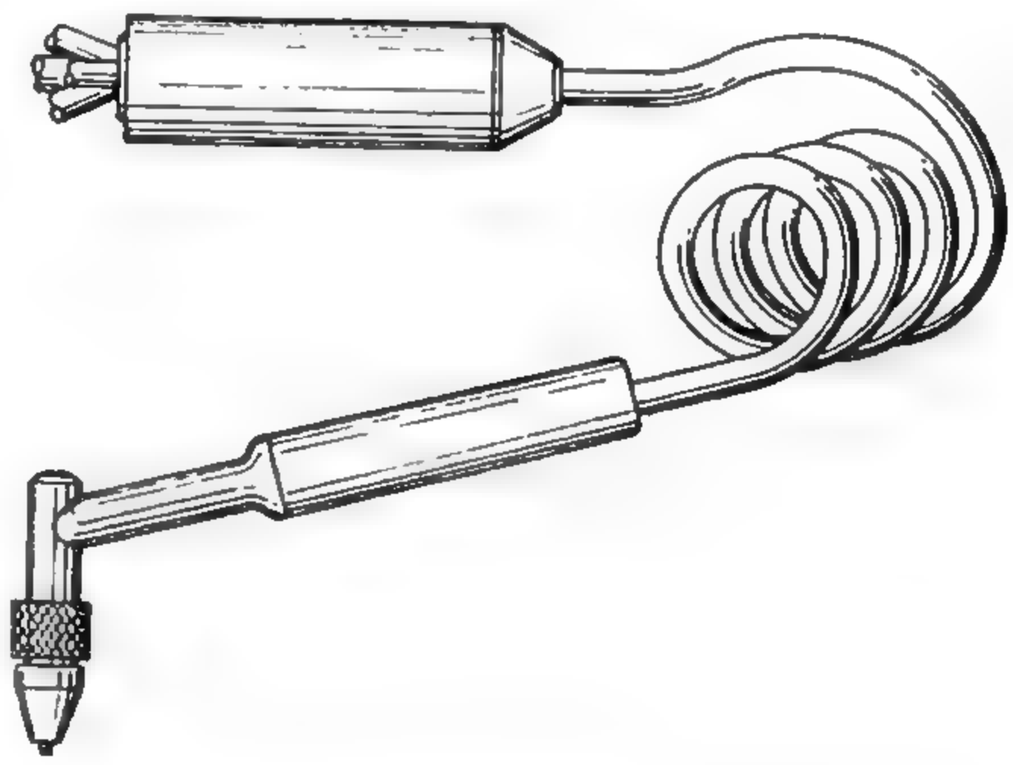

Fig. 16.—Manual Water-Cooled Inert-Gas Metal-Arc Welding Electrode Holder

arcing to parts of the electrode holder itself.

Electrodes have been held by set screws, by brazed joints and by collets. Set screws are not generally used in commercial electrode holders because of the difficulties in making adjustments of the position of the electrode in the holder. Collets, either of the spring type or with positive clamping nuts, are usually used. Brazed joints between tungsten electrodes and copper contact parts have been used for very high currents such as 800 to 1000 amperes.

Proper gas shielding is one of the most important requirements of inert-gas metal-arc electrode holder. Both ceramic and metal nozzles are in use. Ceramic nozzles have the advantage of freedom from arcing when used with radio frequency pilot circuits, since they are of insulating materials and they are light in weight. Ceramic nozzles, however, are relatively fragile either from the mechanical standpoint or when exposed to very high temperatures and they also are likely to permit diffusion of the shielding gas outward or diffusion of contaminating air inward. Some types are likely to pick up spatter from the molten pool of metal with consequent reduction

in their melting point and rapid disintegration.

Metal nozzles can be used at very high currents if they are properly water-cooled. They have the advantage of thin section which permits tapering the outside to give maximum visibility of the work and molten pool. Spatter does not stick to them as easily as it does to ceramics. Metal nozzles must be insulated from the live parts of the electrode holder in order to prevent arcing from the nozzle to the work. This may be troublesome where high frequency pilot stabilization is employed.

Welding Cable Length.—Since electrical conductors of very small cross section and consequent high watts loss per foot of length are used with inert-gas metal-arc electrode holders for reasons of lightness and flexibility, it is desirable to avoid the use of long cable lengths. Excessive voltage drop and wasted power result from very long cables. In addition, where high-frequency pilot circuit stabilization is employed, it is difficult to obtain adequate arc stabilization with a long welding lead because of the electrical capacity between the electrode lead and ground, which bypasses the radio frequency energy. Similarly, long leads introduce excessive water-pressure drop so that it may be difficult to secure an adequate flow of cooling water without going to pressures which are too high for the light, thin-walled tubing used with such electrode holders.

Except where radio frequency stabilization is concerned, these limitations can be overcome by running separate electrical power cable, gas hose and water hose to a terminal block, at which point they can be combined into a light hose and cable assembly running to the elcetrode holder. In the separate extensions thus provided, lightness is of no consequence and a copper conductor of heavy cross-section can be used, along with standard weight water and gas lines.

In connection with hoses, it should be observed that there is some tendency, particularly with helium, toward diffusion of contaminating air into gas lines, even though the pressure of the gas is greater than that of the outside air. Natural rubber is therefore not considered to be the best material for gas hose; some of the synthetic materials are much more satisfactory.

Electrodes

Carbon electrodes are generally limited to use when welding with low currents. Easy arc starting and good arc stability favor their use. Their relatively high rate of consumption and the fact that they are very easily broken are adverse factors.

Tungsten electrodes are much more widely used because they have higher current-carrying capacities in small diameters, they are much more durable and, when properly operated, do not contaminate the weld. Tungsten electrodes are commonly available in a wide variety of diameters and lengths, and with three kinds of surface treatment. Swaged type, or graphite finish, electrodes are widely used because of their somewhat lower cost. They are coated with a graphite film, resulting from manufacturing operations, and since they do not run as close to dimension as centerless ground electrodes, they introduce some problems in gripping and introducing high welding currents. Polished tungsten electrodes are similar to the graphite finish type except that they have been tumbled to give them a bright, clean surface. Centerless ground tungsten electrodes are usually recommended for inert-gas metal-arc welding because surface imperfections have been removed by grinding, and they generally meet a tolerance of plus or minus 0.001 in. variation in diameter. This facilitates slipping them in collets which are tight enough to give good electrical contact.

The current carrying capacity of tungsten electrodes depends on a number of factors such as the type of shielding gas used, the length of tungsten extending beyond the collet, the effectiveness of the cooling afforded by the electrode holder, the position of welding and the polarity of the current. A marked difference is observed in the current capacity of electrodes with straight polarity d.c. and reverse polarity d.c. or a.c. as indicated in Table 5.

While Table 5 gives usable current ranges on various sizes of electrode, considerable care must be exercised in choosing the relationship of current to tungsten diameter for a given job. The primary objective is to select a current which can be used with the tungsten electrode at the highest possible temperature

Table 5—Current Ranges for Tungsten Electrodes, Amp.

Electrode Diam., In.	—A.C. Without D.C.— Component Helium	Component Argon	A.C. (Unbalanced) Argon[a]	D.C. Straight Polarity (Helium)	D.C. Reverse Polarity (Either Gas)
0.010	..	Up to 15	...	Up to 6	..
0.020	..	10– 20	...	15– 25	..
0.040	..	20– 30	...	20– 50	..
1/16	25– 30	30– 80	40–120	50–150	10– 20
3/32	30– 50	60–130	100–180	100–250	15– 30
1/8	40– 80	100–180	150–225	200–300	25– 40
5/16	50–150	180–300	250–325	275–350	40– 80
1/4	60–250	250–400	300–450	300–450	80–125

[a] See note on page 183 regarding methods of measuring unbalanced alternating currents.

consistent with long electrode life. Too high a current density with helium may result in a black deposit of tungsten on the work. Too low a current density results in an arc which is hard to direct, may be very hard to establish and which sometimes runs up the side of the electrode striking to the collet.

With balanced wave a.c. (using argon) a good rule of thumb is to use 25 amp. plus 1 amp. for each 0.001 in. of electrode diameter. With straight polarity, d.c. and argon, these values can be increased by 50%. Figure 17 graphically shows current levels which have been found satisfactory for manual welding. These curves are based on empirical data for one design of electrode holder. The maximum current capacity of an electrode depends on a large number of factors so that these curves are only approximate.

Electrode life is usually longer if proper operating conditions are employed. The useful life of a 3- or 4-in. tungsten electrode may be from one to six weeks. Electrodes 5/16 in. in diam. and 3 in. long have been used for as long as two months in regular 8-hr. shifts at 550 amp. a.c. with argon-shielded, machine welding of aluminum.

Factors which shorten tungsten electrode life are:

1. Operation at too low current density resulting in *cathode bombardment* and erosion due to low temperature.
2. Operation at too high current density, resulting in excessive melting and dripping.
3. Oxidation, usually during the cool-

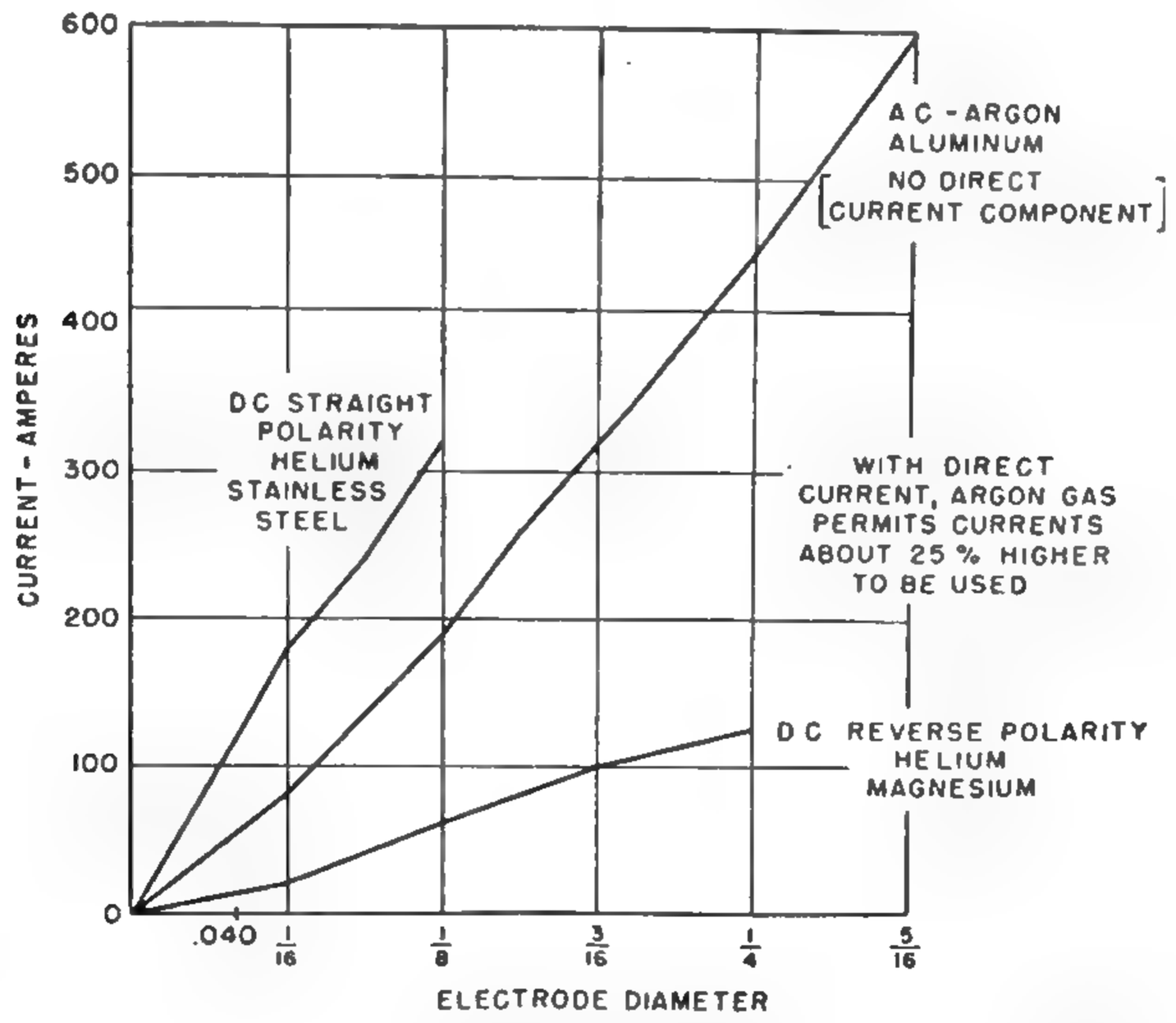

Fig. 17.—Current Levels Satisfactory for Manual Inert-Gas Metal-Arc Welding

ing period, because of too early shutting off of gas flow. Tungsten electrodes when cool should show a mirror-bright arcing end.

4. Contamination with base metal, particularly aluminum, due to contact of hot electrode with welding rod or base metal.

Gases

High gas purity is essential to successful arc welding in either helium or argon atmospheres. Argon is usually specified as *welding grade argon, 99.8 ratio.* The purity of helium has gradually been increased by the Bureau of Mines, which produces it, to a nominal value of 99.7%. In actual analysis, helium in clean cylinders will show better than 99.9% purity.

Argon is commercially obtainable in cylinders of 200 cu. ft. volume under 2000 psi. pressure at 70°F., weighing 154 pounds.

Helium is commerically obtainable in cylinders of 235 and 187 cu. ft. volume under pressures of 2415 and 2215 psi., respectively, and weighing 135 and 92 lb., respectively.

Auxiliary Equipment

Auxiliary equipment used in inert-gas metal-arc welding includes gas regulators flow meters and filler metal feeders.

A two-stage pressure regulator specially designed for inert gas control and including a small flow meter and a gage to indicate gas cylinder pressure is shown in Fig. 18. Some regulators are equipped with an additional gage to indicate the pressure of the gas being delivered by the regulator. This is the back-pressure on the regulator or flow meter. The back pressure may be raised by throttling the gas flow to the electrode holder by means of a needle valve.

The back pressure is important where maximum accuracy of the flow meter is desired because it affects the density of the gas. Flow meters are designed or calibrated for a specific gas at a specific pressure; the use of oxygen-therapy or other flow meters not designed for helium or argon will therefore give misleading readings. Flow meters are usually calibrated in liters of gas per min. or cu. ft. per hr. (1 liter per min. is approximately equal to 2.1 cu. ft. per hr.).

For laboratory testing or when reliable measurement of gas flow is required, either displacement-type gas meters or laboratory-type flow meters operated with carefully regulated pressure should be used. These are available as separate units with a variety of mounting arrangements, and can frequently be put into the same cabinet with other control equipment.

Filler Metal Feeders.—Filler metal feeders designed particularly for feeding small-diameter welding rods at extremely uniform speeds are frequently useful in machine-welding installations. The primary considerations in building this equipment are uniformity of speed in spite of load changes, wide speed range and ability to feed small wires without kinking or jamming them in the delivery tube or nozzle.

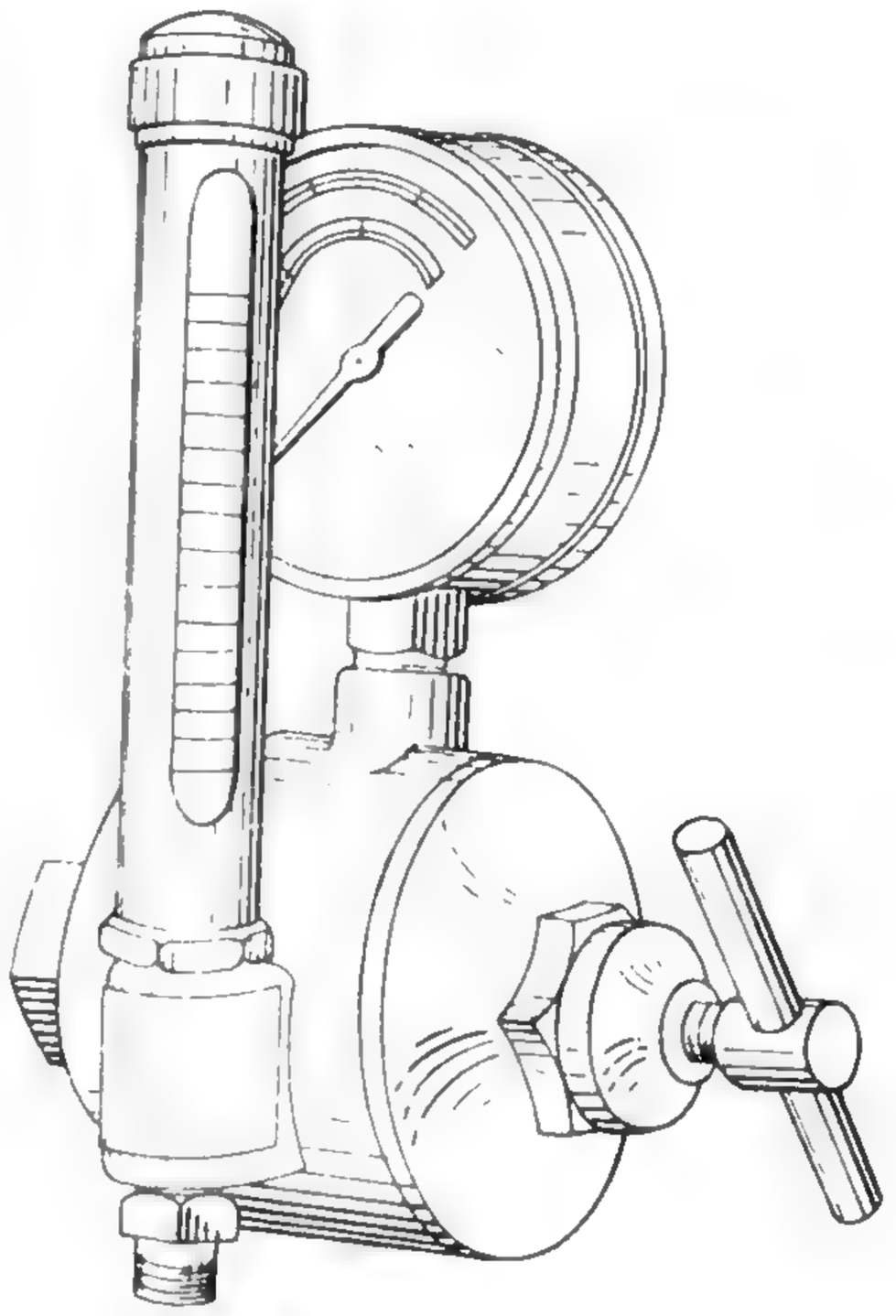

Fig. 18.—Two-Stage Regulator and Flow Meter for Inert-Gas Metal-Arc Welding

Mounting arrangements should provide very close adjustment of the angle and position of the issuing welding rod relative to the electrode. Very slight changes in these factors will make large differences in the speed and effectiveness with which filler metal can be added to the molten pool. Contact of the filler metal with the electrode must always be avoided, as it will result in a wild, explosive arc action and contaminated electrodes

Machine Welding Equipment

For mechanized inert-gas metal-arc welding, special electrode holders are available, usually straight and often arranged for mounting on machine oxygen-cutting equipment. Water-cooled electrode holders of this type have been built with capacity for electrodes up to $^1/_2$ in. in diam. and welding currents of 800 to 1000 amperes. Some designs provide means for introducing an axial magnetic field to reduce the tendency of the arc to wander. Water cooling of gas nozzles is essential for high-current ratings.

Automatic welding heads, which may employ the same general type of electrode holder or special built-in designs, provide continuous and automatic adjustment of the welding arc length in response to slight changes in arc voltage. They are usually used for helium-shielded, d.c. inert-gas metal-arc welding. Argon introduces some difficulties because with it the arc voltage is almost constant over the working range of arc lengths.

as required to maintain the preset arc length. Transverse adjustment of the electrode relative to the joint is provided to permit accurate following of the seam.

See Chapter 12 for information on inert-gas metal-arc welding.

C. ATOMIC HYDROGEN ARC-WELDING EQUIPMENT

ATOMIC HYDROGEN WELDING MACHINES

Machine Ratings

Standard atomic hydrogen arc-welding machines are of the a.c., single-phase, static-transformer type and are made with ratings and approximate characteristics as shown in Table 6.

35-amp. rated welding machines, with their associated electrode holders and auxiliary equipment, are ordinarily used for light, manual job shop welding, for welding thicknesses up to $^3/_{32}$ in., mold

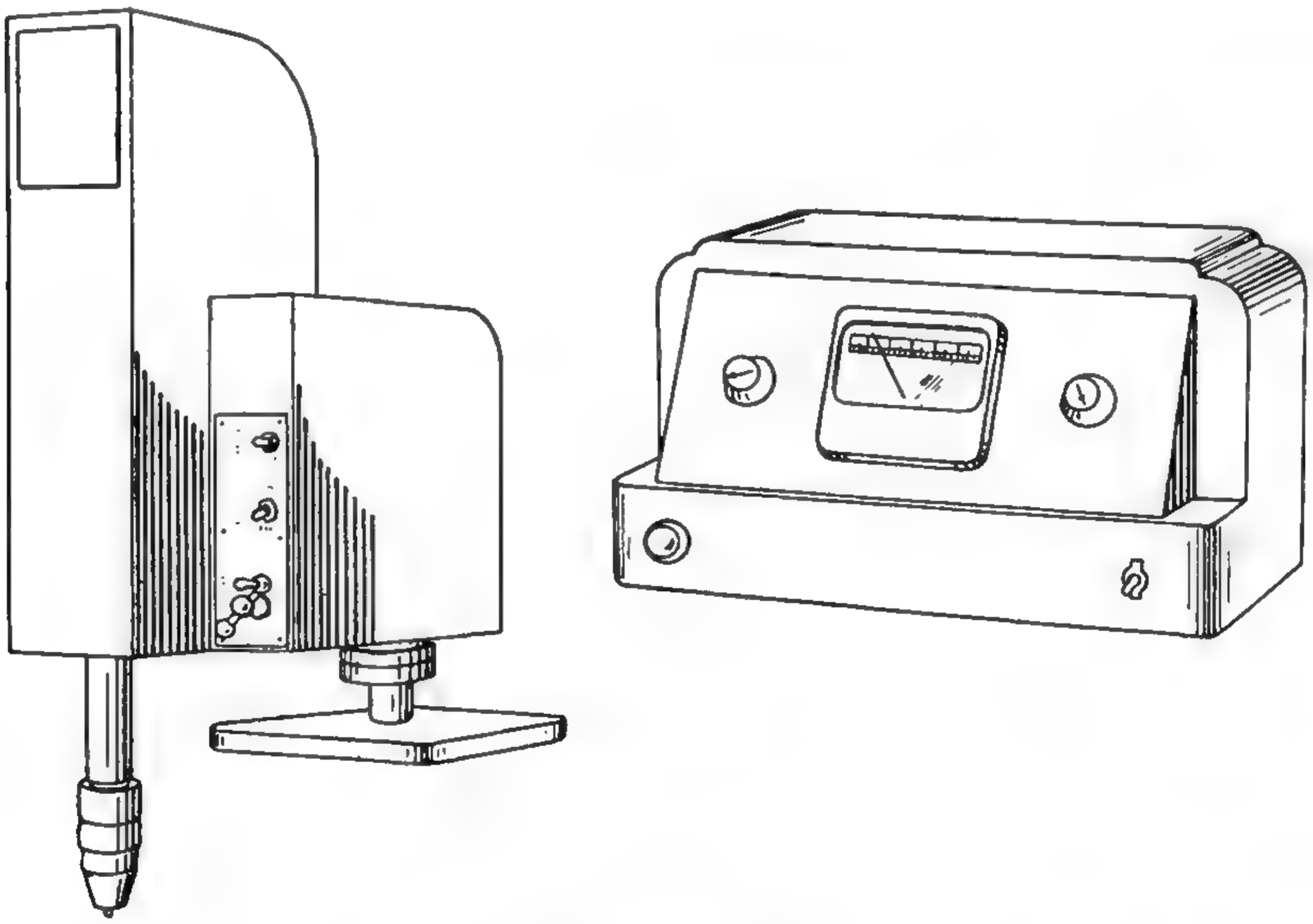

Fig. 19.—Automatic Inert-Gas Metal-Arc Welding Head with Control for Maintaining Constant Arc Length

Figure 19 illustrates one form of automatic inert-gas arc-welding head and its associated control panel. This equipment uses electronic control of a motor which moves the electrode holder up or down

and die work, and laboratory uses.

75-amp. rated machines are the most commonly used in general job-welding shops and production welding. They can be used for manual welding in almost any

thickness of material, and machine welding of parts up to approximately $^1/_2$-in. thick.

150-amp. rated welding machines are commonly used only on highly specialized manual work, such as overlaying of hard materials, and on heavy-duty, high-speed machine-welding applications.

Table 6—Ratings and Characteristics of Atomic Hydrogen Arc-Welding Machines

Rated Output Current, Amp.	Rated Duty Cycle, %[a]	Current Input at 440 Volts, Amp.	Power Input at Rated Load, Kw.	Power Factor at Rated Load
35	60	13	5	0.88
75	60	27	10	0.81
150	Continuous	55	19.5	0.80

[a] Duty cycle is based on 10-min. total time cycle, or 6 min. load out of each 10 min. elapsed time.

Power Supply

Welding machines for 50- and 60-cycle power supply are common; special units for use with 25-cycle power have been built. Single-phase windings are universally used. Two or more units may be distributed on different phases of two- or three-phase supply systems.

Good power factor is afforded in modern units by built-in power factor correcting capacitors. These improve the otherwise low power factor which would result from the relatively high reactive voltage drop used to facilitate striking and maintaining a stable arc. Power factors usually range from 0.2 leading at minimum current settings to 0.6 lagging at maximum.

Special Requirements

Successful atomic hydrogen arc welding cannot be done with standard shielded metal-arc, a.c. welding machines. Special requirements include high induced voltage, zero-voltage idling control and an auxiliary starting winding. Figure 20 illustrates typical connections and the principles of the control scheme. The transformer has secondary windings for the main welding power, auxiliary starting power, power to operate a cooling fan and a control voltage which is in phase with the welding terminal voltage. Pressing the *start* push-button energizes contactors *M* and *B* and the solenoid valve, applying voltage to the welding terminals and opening the hydrogen valve. When

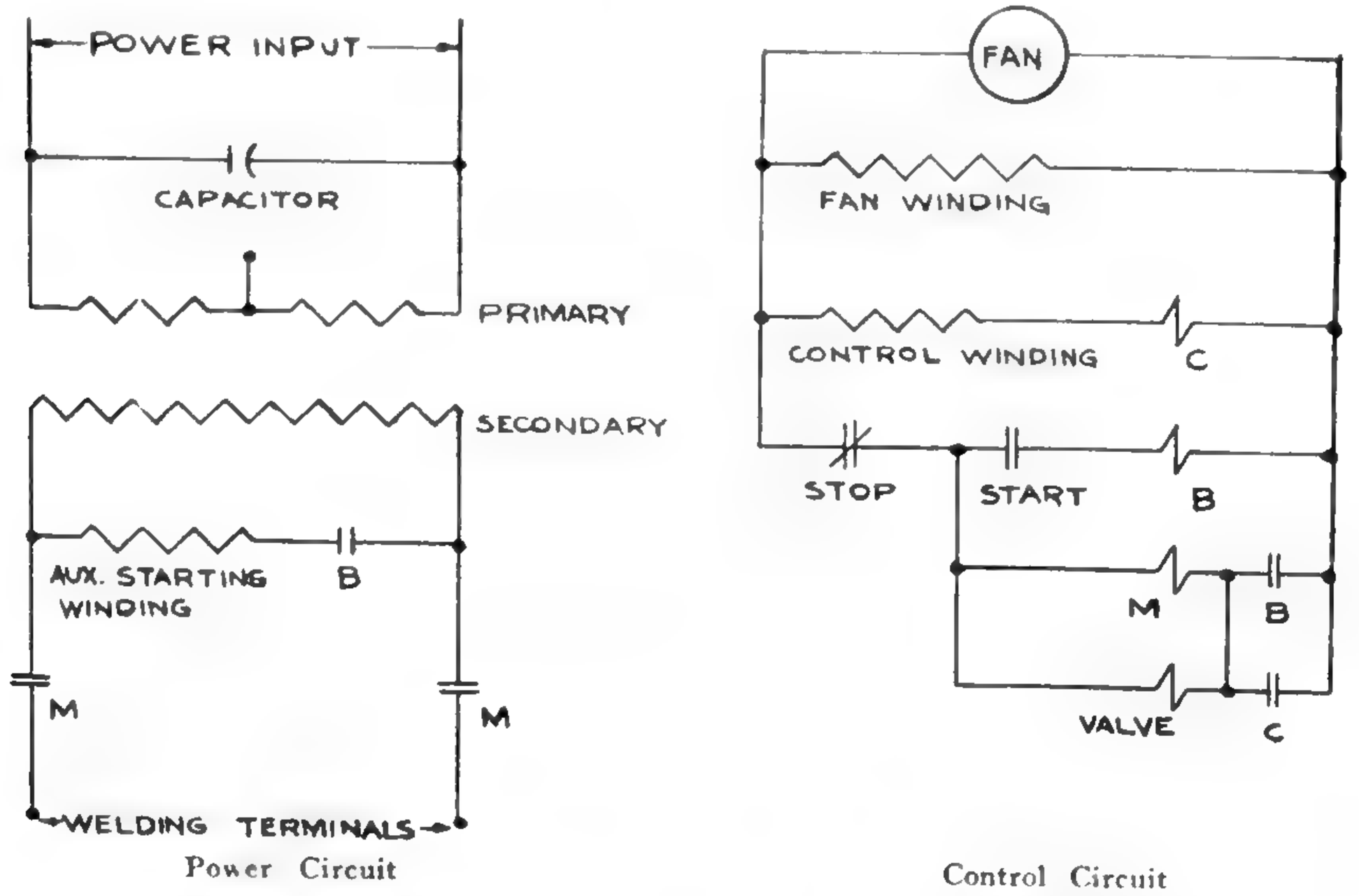

Fig. 20.—Schematic Wiring Diagram for Atomic Hydrogen Welding Machine

the arc is struck, the phase angle of the control winding shifts, causing the phase difference voltage between the fan winding and the control winding to energize contactor *C*. The contacts of *C* seal in main contactor *M* and the solenoid valve. Contactor *B* drops out, disconnecting the

auxiliary starting winding, as soon as the *start* button is released.

The arc is stopped by depressing the *stop* button which opens the main contactor, or by lengthening the arc until it breaks. This puts the control winding voltage in phase with the fan winding voltage so that contactor *C* is de-energized. Its contacts open the main contactor coil and solenoid valve circuits.

AUXILIARY EQUIPMENT

Electrode Holders

Specially designed electrode holders are used for manual atomic hydrogen arc welding. Commonly used sizes have current ratings and electrode capacities as shown in Table 7 and are usually used with welding machines having corresponding ratings selected from Table 6.

Table 7—Atomic Hydrogen Electrode Holders

Rated Current, Amp.	Electrode Diam., In.
50	0.040 or 1/16 or 3/32
75	3/32 or 1/8
100	1/8 or 5/32

Electrodes

Tungsten electrodes are available in a range of diameters from 0.040 to 3/10 in., nominal sizes being in 1/32 of an inch. For manual welding, 12-in. long electrodes are usual, which may also be used for machine welding in diameters up to 1/8 inch. In the larger diameters, using lengths of 2 to 5 ft. results in some economy in machine welding. Electrodes may be obtained in three types of finish, usually called *graphite*, *polished* and *ground*, with cost increasing in the order given. The graphite finish is that resulting from drawing or swaging operations. When the die lubricant and surface oxide are removed by buffing, the polished finish is the result. The ground finish is obtained by centerless grinding and results in a smooth contact surface and a minimum of eccentricity. In the majority of applications, either the graphite or polished finish is completely satisfactory. Where the electrode may be subjected to high current densities, the lower contact resistance of the polished or ground finish may be desirable. Where both low contact resistance and low eccentricity are factors, the ground finish may be necessary.

Hydrogen

Hydrogen is commercially available in tanks or cylinders usually containing approximately 200 cu. ft. at a pressure of approximately 2000 psi. (The volume given is at atmospheric pressure.) If the quantity of gas used is sufficient to justify the capital investment, equipment may be installed for the dissociation of anhydrous ammonia into hydrogen and nitrogen by passing it through a suitable furnace, called an ammonia dissociator.

The pressure of the stored hydrogen is usually higher than that required for welding. For this reason, as well as to insure a fairly constant welding pressure, a pressure regulator is inserted in the line, usually attached to the hydrogen tank. A regulator having a high-pressure gage with a scale to suit the supply and a low-pressure gage with a scale of 0 to 50 psi. is recommended.

In the majority of cases, the atomic hydrogen welding machine includes a solenoid-operated valve, which opens to allow the flow of hydrogen when the electrical circuit is energized, and closes when it is de-energized.

Further information, including a description of machine atomic hydrogen welding equipment will be found in Chapter 11.

D. SUBMERGED ARC WELDING

Besides the granular material, or flux, and the electrode, or filler rod, which are described in Chapter 13, submerged arc welding requires a source of welding power and an automatic or semi-automatic welding head.

Power sources may be either a.c., transformer-type arc welding machines or motor-generator type, d.c. arc welding machines, described at the beginning of this chapter. Some special considerations apply to the selection of these units for submerged arc welding because of the high currents and high arc voltages frequently encountered in this process. Arc voltages usually range from 20 to 55 volts

SUBMERGED ARC-WELDING MACHINES

Alternating-Current Machines

For a.c. welding machines the major factors to be considered are special control features, high currents and high arc voltages. Special control contactors may be built into the welding machine enclosing case or furnished on separate panels. For machines of the larger NEMA ratings (see Table 1) contactors are usually built in, along with disconnecting knife switches and fuses or circuit breakers.

Motor-operated current adjusters, usually actuated by push buttons at the welding operator's station, are frequently used for convenience. This permits locating the welding machine out of the way, without entailing lost time in making adjustments.

The required welding current capacity may exceed the largest NEMA standard arc-welding machine (1000 amp.), in which case two or more units may readily be paralleled to supply the necessary current (see page 182). Installations of 4 or 5 welding machines of 500-amp. rating operated in parallel are frequent.

The high arc voltages require the use of welding-machine circuits of sufficiently high induced voltage to prevent extinguishment of the arc and excessive changes in arc current due to small changes in arc voltage. Welding machines with induced (open-circuit) voltages of 75 volts or over are usually employed.

Direct-Current Welding Machines

The characteristics of standard d.c. arc-welding machines are well suited to submerged arc welding. In addition to the standard NEMA ratings which may be paralleled to obtain the necessary current capacity, special units of 1200-amp. rating are available. These usually consist of two 600-amp. generators driven by a single a.c. motor and connected in parallel.

The high arc voltages of some submerged arc applications will be reflected in additional load on the motor driving the generator. At a given current, the input to the generator is roughly proportional to the load voltage of the generator. Care should be taken to select units having sufficient motor rating whenever load voltages (arc voltage plus voltage drop in cables) exceeding 40 volts are anticipated

The flow of d.c. welding current is started and stopped either by means of a large contactor in the welding circuit or by means of a small contactor in the generator field circuit, depending on the characteristics of the generator.

WELDING HEADS

Automatic Heads

Automatic welding heads used in this process are generally similar to those employed in shielded metal-arc welding and the same control schemes are used. Flux-dispensing hoppers and tubes are usually attached to the welding heads, and special current conducting members may be required to introduce high welding currents into the electrode, without excessive heating

Either reversing or non-reversing welding heads may be used. With the former, the arc is established when the start button is depressed by rapid reversal of the welding head motor when the electrode touches the work. This draws an arc, after which the motor feeds the electrode in the usual way.

When non-reversing control schemes are used, the arc is struck by a high-voltage, high-frequency spark discharge, or by initially interposing a wad of steel wool, or a piece of carbon between the electrode and the work before welding power is applied to the electrode. In either case, the electrode is not advanced toward the work until after the arc is established. (See Chapter 13).

Semi-Automatic Equipment

Semi-automatic or manually controlled submerged arc-welding equipment involves similar control and electrode feeding functions. However, the electrode is delivered through a flexible conductor so that the operator may direct the electrode to follow a seam and control the rate of advance along it (see Chapter 13).

Manual Equipment

Manual submerged arc-welding equipment is similar to that used in the semi-automatic installations, except that the electrode is advanced out of an electrode-guiding tool by the feed motor at a preset constant speed. No control responsive to arc voltage is employed. Arc length is controlled by the welder who raises or depresses the tip of the electrode

as the need is indicated by a volt meter mounted on the electrode guide.

E. STUD WELDING EQUIPMENT

In general, stud-welding equipment consists of a gun or stud holder, usually air or solenoid operated, a control panel for controlling the welding current, and a source of welding power, which to date has been d.c. almost without exception.

TYPES OF GUNS

Two types of stud guns are in use. In one the end of the stud is placed in contact with the work, welding power is applied and a solenoid energized by the welding current draws the stud away from the work to a predetermined distance. After a preset arcing time measured in tenths of a second, the control automatically interrupts the welding current. The solenoid is de-energized and a spring drives the stud into contact with the work. This equipment and modifications for bench and production applications together with a discussion of its use are described in detail in Chapter 14.

In the percussion type stud gun, the timing of the arc is controlled by the speed with which the stud is moved toward the work and by the dimensions of a small diameter projection on the end of the stud. The stud moves toward the work in a continuous motion. As the projection meets the work, welding power flows, the projection is vaporized and an arc takes place as the stud is driven onto the work and the weld is completed. Arcing time is regulated by the length and geometry of the projection and by the air pressure supplied from a small reservoir charged to a predetermined pressure through a regulator.

CONTROLS

Controls for stud guns are specially designed contactor and relay panels. Accurate timing is very important to the successful operation of solenoid-operated stud welding guns. Control panels for this type of gun are described in Chapter 14.

Panels used with percussion stud guns are made in a variety of forms to suit the type of welding power supply equipment used. Those for use with arc-welding generators are designed to close the field circuit to the generator and to close the main contactor in the welding circuit when the trigger is depressed to start the weld cycle. As soon as the main contactor closes, a field contactor opens the generator field to reduce the short-circuit current through the stud, immediately followed by opening of the main contactor.

Control equipment necessary with rectifier-capacitor welding power units is incorporated in the power unit assembly.

WELDING POWER SOURCE

For the solenoid-operated stud gun system, standard single-operator, motor-generator type, d.c. arc-welding machines are employed. For this service welding machines must be maintained properly, particularly with regard to commutator and brush condition. Units which have high maximum motor breakdown torque are preferred, in order to prevent drooping currents due to the overloads occurring during welding. Welding machine capacities under normal operating conditions are shown in Table 8 for solenoid-operated stud guns.

Table 8—Welding Machine Ratings for Stud Welding

Stud Diam., In.	Welding Machine NEMA Rating, Amp.
Up to 3/8	300
1/2	400
5/8	two-400 paralleled
3/4	three-400 paralleled

For percussion stud guns, welding power circuits of very high instantaneous current output are highly desirable. Standard single-operator, motor-generator, d.c. arc-welding machines may require slight modification in order to assure the maximum rate of rise of current on short circuit. Welding machines having reactance coils which can be readily short-circuited are suitable. Other types of machines may require changes in field connections. Commutating conditions of

the generator should be carefully observed, as unusually high surges of current may cause aggravated sparking at the brushes. Unless this is excessive, the running-light intervals between welds in normal duty cycles should serve to restore good commutator polish.

Rectifier-capacitor power units have been used with good results in percussion stud welding. An electronic tube rectifier circuit energized from the single-phase, a.c. supply furnishes direct current to charge a capacitor of very large electrical capacity, such as 30,000 or 40,000 microfarads. When the charged capacitor is connected to the stud, extremely high discharge currents of short duration are produced. Some installations have used similar arrangements except that the capacitors are charged by a single-operator, motor-generator type, d.c. arc welding machine.

F. CARBON-ARC WELDING EQUIPMENT

WELDING MACHINES

Capacity and Ratings

Welding machines for the automatic use of carbon-arc welding are manufactured in one size and model, but provide a range of control that permits their application to a wide variety of jobs. This machine will weld with a current ranging from 100 to 1000 amp. and can be used for metal thicknesses from 16 ga. to 1 inch. The head can be adapted to use $^1/_4$- to $^1/_2$-in. carbon electrodes. The same equipment is used for welding both ferrous and non-ferrous metals. A typical carbon-arc welding head is illustrated in Chapter 9.

Welding Head Controls

The automatic carbon-arc welding head is a mechanism for holding a carbon welding electrode, automatically striking the arc, automatically feeding the electrode so as to maintain a constant arc voltage at all times, and rotating the electrode to keep it symmetrically pointed. An electro-magnetic field introduced around the arc is used to direct the force of the arc and to vary the welding characteristics of the arc.

The carbon electrode is held in a fiber tube, the inside of which is drilled to the proper diameter. The holder has a row of gear teeth along one side so that it can be fed through a feeder body that is contained in the case of the welding head. The feeder body strikes the arc by moving the carbon holder up or down, rotates the holder and feeds the electrode into the arc as necessary. The feeder body is driven by an electric motor that is an integral part of the head.

The feeder body assembly consists of a set of differential gearing provided with friction drums. If both drums are allowed to rotate freely they will rotate at the same speed and the electrode holder will not be raised or lowered. If the upper drum is retarded, the electrode holder will be fed upward; if the lower drum is retarded, the electrode holder will be fed downward. Each drum is provided with a magnetically operated brake for controlling the operation of the holder. These brakes are controlled by a differential relay mounted in a control panel.

The differential relay consists of an armature suspended on flat springs so as to float freely inside a set of differential coils. The armature operates a set of contacts at each end. The coils on the right hand are connected across the arc; the coils on the left hand are connected across the constant potential control circuit through an adjustable rheostat. With the rheostat the voltage across the left-hand coils can be set to any desired value up to 50 volts. The voltage across these coils is known as the *reference voltage* and is indicated on a meter.

The two sets of coils are connected in opposition to each other so that when the arc voltage is exactly equal to the reference voltage, the armature remains in its central position and neither contact is closed. If the arc voltage exceeds the reference voltage, the armature swings to the right, closing the contact, energizing the down-feeding brake coils in the head, which causes the arc to be shortened until the arc voltage is just equal to the reference voltage.

If the arc voltage is less than the reference voltage, the relay swings to the left energizing the up-feeding brake coils causing the arc to be lengthened. Thus

the differential relay keeps the arc voltage and, consequently, the arc length at a constant value, which is determined by the setting of the reference voltage. In actual operation the armature vibrates rapidly from side to side.

A time delay switch is employed to delay the head travel to allow for proper establishment of the arc and to insure the proper penetration at the start of the weld.

Filler Metal Feed.—When additional filler metal is needed to build up reinforcement or fill in a large joint, a filler metal feeder attachment is added to the standard head equipment. The feeder consists of a set of motor-driven rolls and guides for automatically taking flat or round filler strip or wire from a coil and feeding it into the arc. Speed of metal feed can be varied by a rheostat and direction of feed can be reversed when desired. The feeder and wire coil are insulated from the head and from ground, except where the filler metal touches the work at the arc.

Flux Feeding.—Fluxing and shielding of the arc are accomplished by using either a fibrous or a powdered flux or a paste (see Chapter 9). For powdered flux, a hopper fitted with a feeder drum and valve is attached to the head. The hopper deposits the powder on the seam to be welded directly in front of the carbon electrode.

For fibrous flux another feeder attachment is added which consists of changeable spur gears and drive rolls, and a flux guide tube that can be adjusted to direct the fibrous material into the arc. The fibrous flux is directed so that it touches the side of the carbon and passes directly over the seam. The speed of the flux feed is adjusted with a field rheostat in the head motor. Gears provide a variety of ranges within which the speed can be regulated. The speed is regulated so that the flux is completely burned up after it passes the arc by about 6 to 12 inches.

Current Conduction.—The welding current is conducted to the carbon electrode through a boot or nozzle. The boot is water cooled and within it is wound a coil with a magnetic core for producing the desired magnetic field around the arc. The boots are energized by either a.c. or d.c. depending on the type of arc desired and the nature of the work (see Chapter 9). A twin boot is also sometimes used to direct the force of the arc backward to keep the molten pool away from the arc.

Beam and Carriage

The automatic head may be used in one of several ways. The head itself may be mounted on a beam and remain stationary while the work is passed underneath the arc. The head may also be mounted on a carriage which moves the head along the seam to be welded. The carriage consists of a framework mounted on small wheels and driven by an electric motor through gearing and a drive roller. The carriage is mounted on a beam which can be made any length desired. Limit switches can be put on the beam to interrupt the arc at the desired point. A field rheostat is used to vary the speed of the carriage and gears can be changed to widen the range of the speed variation.

The head may also be mounted on a tractor which is self-powered and can move along a seam without any special track. The head is mounted on a vertical slide so that it can be moved to accommodate a variety of conditions. The speed of travel of the tractor may also be separately controlled.

G. SPECIAL EQUIPMENT FOR MACHINE ARC WELDING

Machine welding by any of the arc-welding processes requires that some or all of the following functions be mechanized:

1. Traversing of the arc with respect to the work.
2. Controlling arc length.
3. Wire feeding.
4. Work holding.

This section discusses the auxiliary equipment necessary for performing these functions; other equipment used for the individual processes is discussed in the foregoing sections of this chapter on the specific processes.

Arc Traversing

Movement of the arc with respect to the work may be accomplished by holding

the work stationary and moving the electrode or vice versa. The choice is usually dictated by convenience and the consideration that practically all machine arc welding is best done in the flat position. Thus, circumferential seams are almost invariably welded with the arc stationary and the work rotating beneath it. Exceptions may be encountered, particularly in inert-gas metal-arc welding.

welding arranged to traverse the head for longitudinal seams and to position the head in desired locations when work-piece is rotated for circumferential seams. The transverse track is motor-elevated; the welding head is supported on a small manually-operated carriage for transverse positioning.

For rotation of the work under the arc, fixturing is frequently combined with the rotating equipment. Figure 22 shows such a

Fig. 21.—Travel Carriage and Positioner for Automatic Shielded Metal-Arc Welding

When the arc is to be traversed, a wide variety of standard *travel carriages* are available. These range from very simple motor-driven cars running on portable tracks as used in gas-cutting equipment to massive structures.

Figure 21 shows a travel carriage and welding head positioner for automatic arc unit arranged to clamp and rotate the work with several different chucks provided to accommodate various size assemblies.

In any arrangement for mechanical traverse, the machine should provide for absolutely uniform travel speed if high quality, uniform work is to be obtained. This point has frequently been overlooked

with bad consequences. It is not enough that the average travel speed over a considerable interval (for example, one revolution of the fixture) should be uniform. The instantaneous variations in speed from point to point along the seam must also be kept to a minimum by proper design to eliminate variable friction, over-running eccentric loads, belt or friction drive slippage and the like.

A wide range of speed adjustment is desirable to permit accommodation of a variety of work and joint preparations. Electronically controlled d.c. motor drive combines the functions of excellent speed regulation and wide speed range.

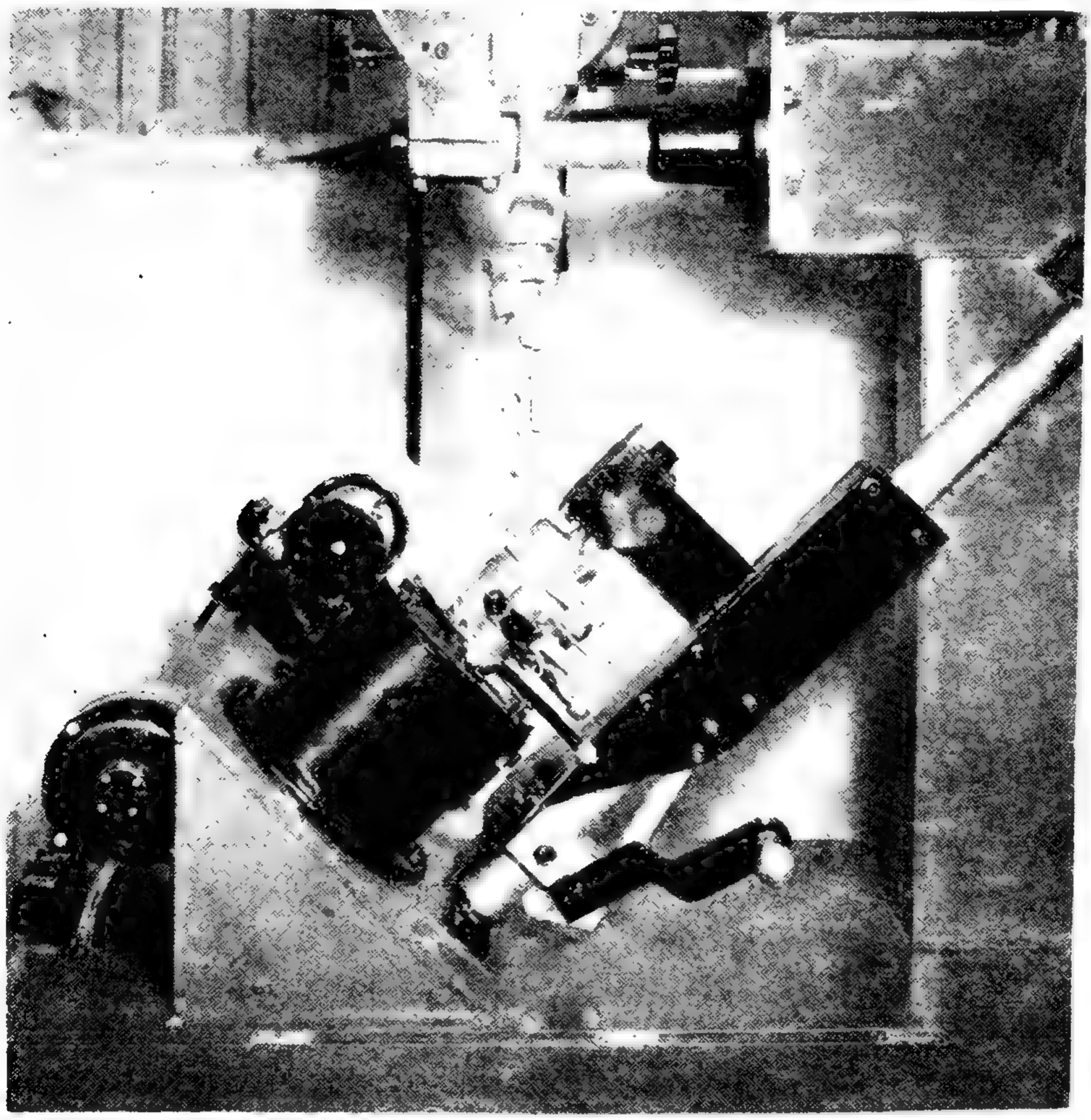

Fig. 22.—Fixture for Rotating and Positioning Assembly for Welding

Arc Length Control

The fundamental characteristic of all automatic arc-welding heads is arc-length control. In processes utilizing a consumable electrode, this function is combined with filler metal feed. In atomic hydrogen and inert-gas metal-arc welding, it is purely a positioning function. In any case, automatic arc-welding heads make use of the fact that arc voltage is a function of arc length. For this reason arc voltage may be used as an indication of arc length and the control system may be designed to maintain arc voltage, and consequently arc length, approximately constant.

Automatic arc-welding heads have been designed around a variety of basic principles. Some types use reversing motors, others operate in only one direction. One design uses two motors, of which one runs at a constant speed, and the other at a speed varying above and below that of the constant speed motor, but always in the same direction. By differ-

ential gearing, this combination can be made to operate the electrode in either direction. Mechanical drive heads have also been developed, one form using air turbines. Another used a constant speed motor with magnetically operated clutches to drive the gearing in either direction and at speeds regulated by the frequency of the rapid engagements of the clutches. Heads utilizing hydraulic or pneumatic actuation of a piston in a cylinder have been proposed for the non-consuming electrode processes.

One reversing motor circuit has the armature of the welding head motor connected in series with the armature of an auxiliary generator, whose field excitation is controlled by the difference between the arc voltage and a reference voltage. If the arc-control rheostat is set for a given arc voltage and the electrode is not being fed at the proper rate of speed to maintain this voltage, thereby causing the arc to become too long or too short, the balance of the system is upset, which changes the voltage applied to the generator field. This change causes the auxiliary generator

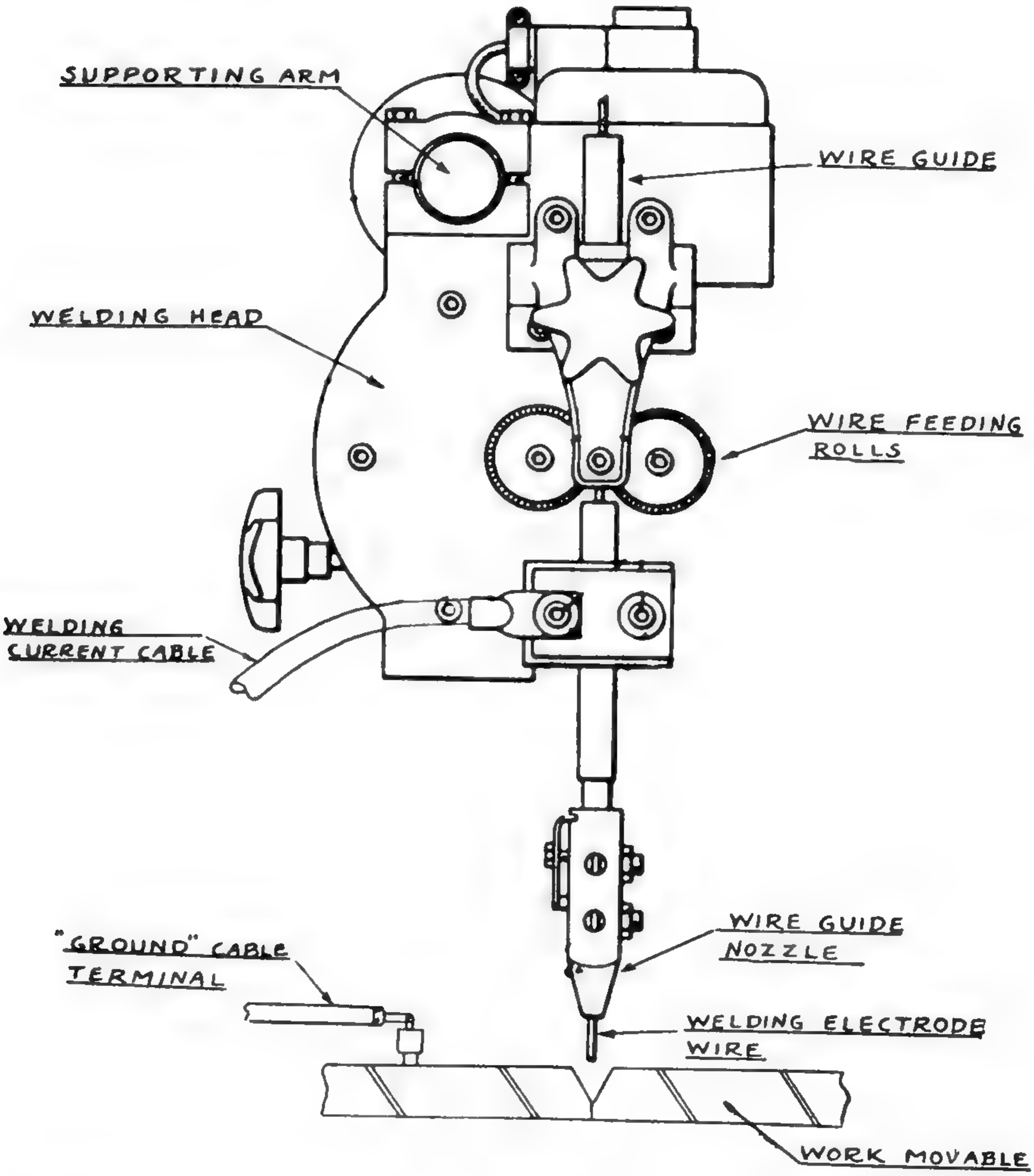

Fig. 23.—Automatic Welding Head for Use with Bare or Lightly-Coated Coiled Electrodes

output to increase or decrease, which in turn causes the feed motor to speed up or slow down until the proper arc length is again maintained. During striking of the arc, the feed motor reverses direction. A control of this type is suitable for applications where wire-feeding is combined with voltage regulation.

Another typical reversing motor control system utilizes thyratron tubes connected back-to-back and feeding the armature of a separately excited d.c. motor. One tube furnishes current, tending to rotate the armature in one direction, while the second tends to reverse the rotation. The amount and direction of the resulting current supplied to the motor armature depend on how much the actual arc voltage is above or below a certain preselected value.

Firing of the thyratron tubes is controlled by shifting their grid phase; this is accomplished by saturable reactors in the grid circuits, whose d.c. windings are supplied by amplified signal currents proportional to the difference between the arc voltage and reference voltage.

Control schemes of this type are used for wire feeding and voltage regulation combined in shielded metal-arc and submerged arc welding. Their sensitivity may be adjusted to make them suitable for the arc voltage control function alone, in atomic hydrogen and inert-gas metal-arc welding where only very slight motion of the electrode is required to increase or decrease the arc voltage.

Wire Feeding

In the shielded metal-arc and submerged arc automatic welding heads, the motor is connected by suitable gearing to friction feed rolls which grip and propel the electrode. The electrode enters and leaves the feed rolls through wire guides. At the lower end of the assembly, means must be provided for introducing the welding current into the electrode.

Bare Metal-Arc Welding Feeders.—The automatic arc welding head for bare and lightly coated electrode is the simplest of the wire feeding automatic welding heads. A typical assembly for this purpose is shown in Fig. 23. Welding heads of this type are used for bare and lightly coated electrodes from $^{3}/_{32}$- to $^{1}/_{4}$-in. diam. which can be supplied in long lengths coiled on reels ranging from 100 to 200 lb. in weight. These heads are

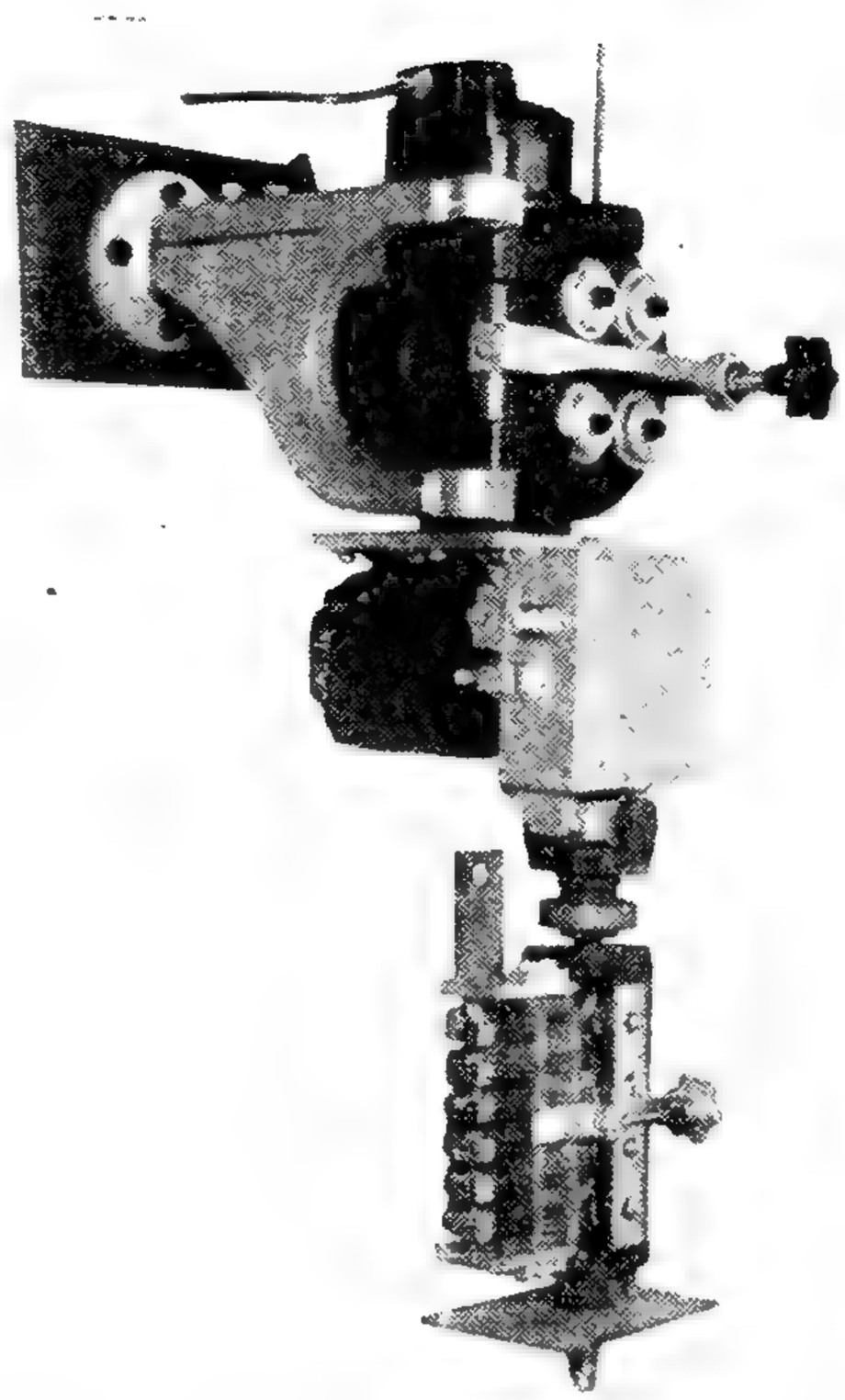

Fig. 24.—Automatic Shielded Metal-Arc Welding Head with Slitter for Making Contact

readily adaptable for submerged arc welding.

Shielded Metal-Arc Electrode Feeders.—Automatic welding heads are available for feeding covered electrodes either from coils or in short lengths. Coiled covered metal-arc electrodes are especially con-

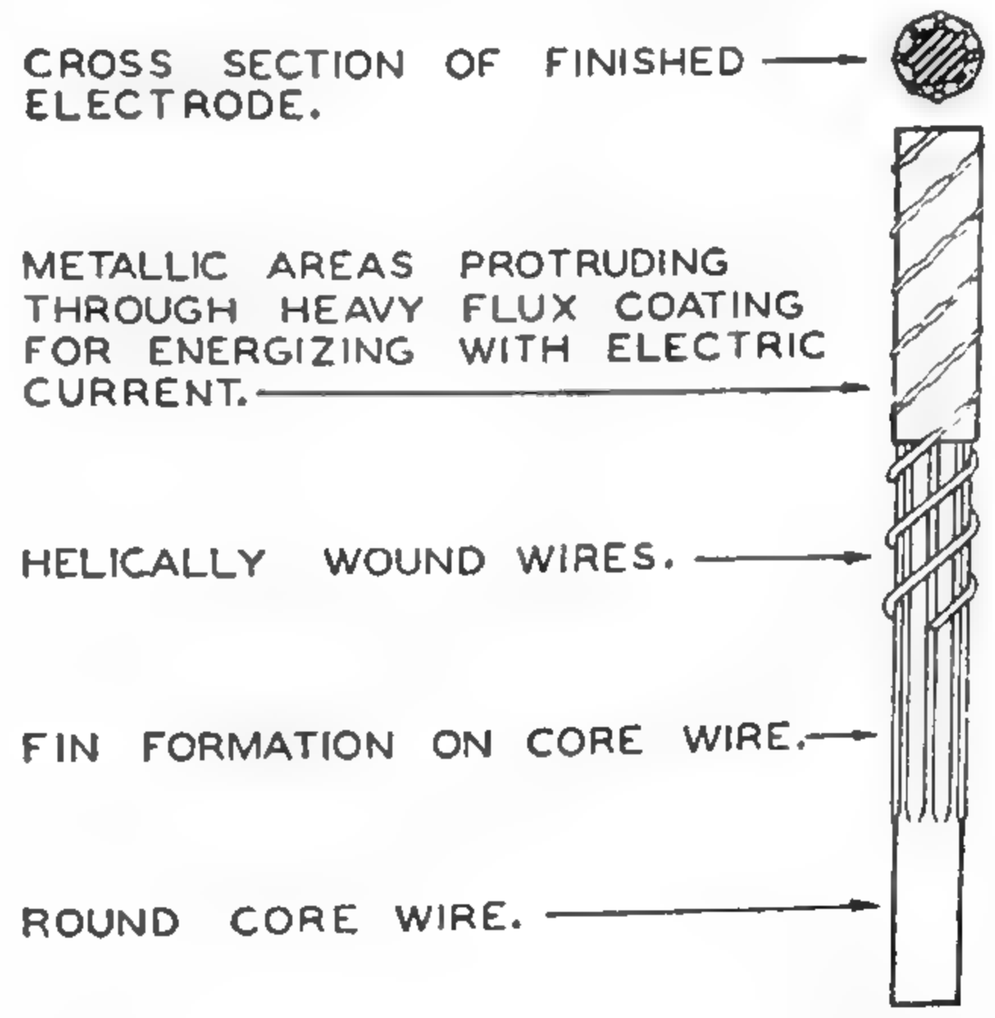

Fig. 25.—A Method of Current Conduction with Covered Coiled Electrodes

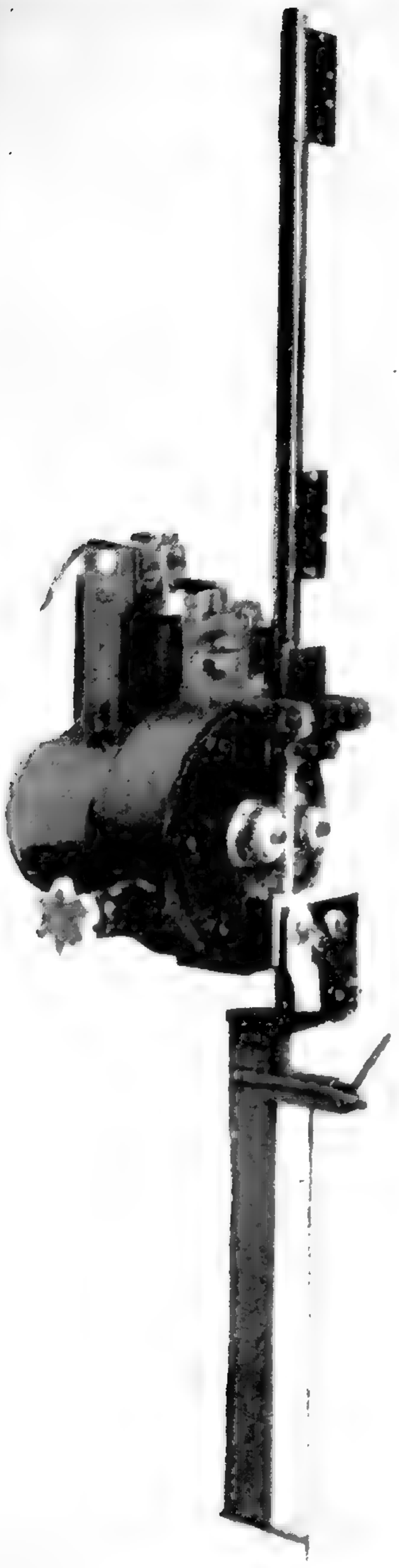

Fig. 26.—Automatic Shielded Metal-Arc Welding Head for Straight Length Electrodes

structed to resist cracking and spalling off of the coating when the wire is curved and straightened. In one type of electrode, the electrode covering is reinforced by spiral threads of asbestos. The welding head feed rolls are rubber faced so that the covering will not be crushed. Current is introduced into the electrode by contact fingers working through a narrow slit milled through the covering by a tungsten carbide, motor-driven cutter. Figure 24 illustrates equipment of this type.

Another type of covered electrode which can be coiled utilizes a spiral wire wound around the core wire and protruding through the electrode covering as illustrated in Fig. 25. When electrodes of this type are used, the slitting function is not required, and current contact jaws can be used.

Automatic welding heads for feeding coiled, covered electrodes are arranged to handle electrodes in sizes from $^{7}/_{32}$- to $^{9}/_{32}$-in. diameter. Current levels are generally 10 to 15% higher than those used with similar sizes for manual welding. The increased current is permissible because of the short length of electrode (between the current contact members and the arc) which is subject to heating by the passage of current.

Automatic welding heads for feeding stick electrodes of the type ordinarily used for manual shielded metal-arc welding utilize the same basic wire feeding mechanism and arc voltage control. In this type of equipment, the motor drives an electrode holder arranged to grip the bared end of the electrode as in manual welding. The range of current usable with heads of this kind is determined only by the manual welding electrodes available. Figure 26 illustrates equipment of this type.

Atomic Hydrogen Arc-Welding Heads.—Atomic hydrogen arc-welding heads are built both as single- and multiple-arc units, the number of arcs depending on the intended application. In these heads, two tungsten electrodes are connected by gearing to a driving motor, and are so arranged that the motor can bring their arcing ends closer together or farther apart as needed to maintain the desired size of arc. Figure 27 illustrates the principles of this welding head. No filler metal feeding is involved in this equipment,

which has the single basic function of arc voltage control. There is no automatic regulation of the distance between the electrode and the work in response to arc voltage. Once this distance is adjusted, however, the regulation of the size of the arc by the arc voltage control does maintain the electrodes at a relatively constant position, so that the heat input to

Current capacities of single-arc automatic atomic hydrogen heads range up to 150 amperes. When more heat is required than can be supplied by a single arc, a multiple-arc head is employed, in which individual motors regulate the pairs of electrodes for each arc, and current adjustment in each arc is independent of the others.

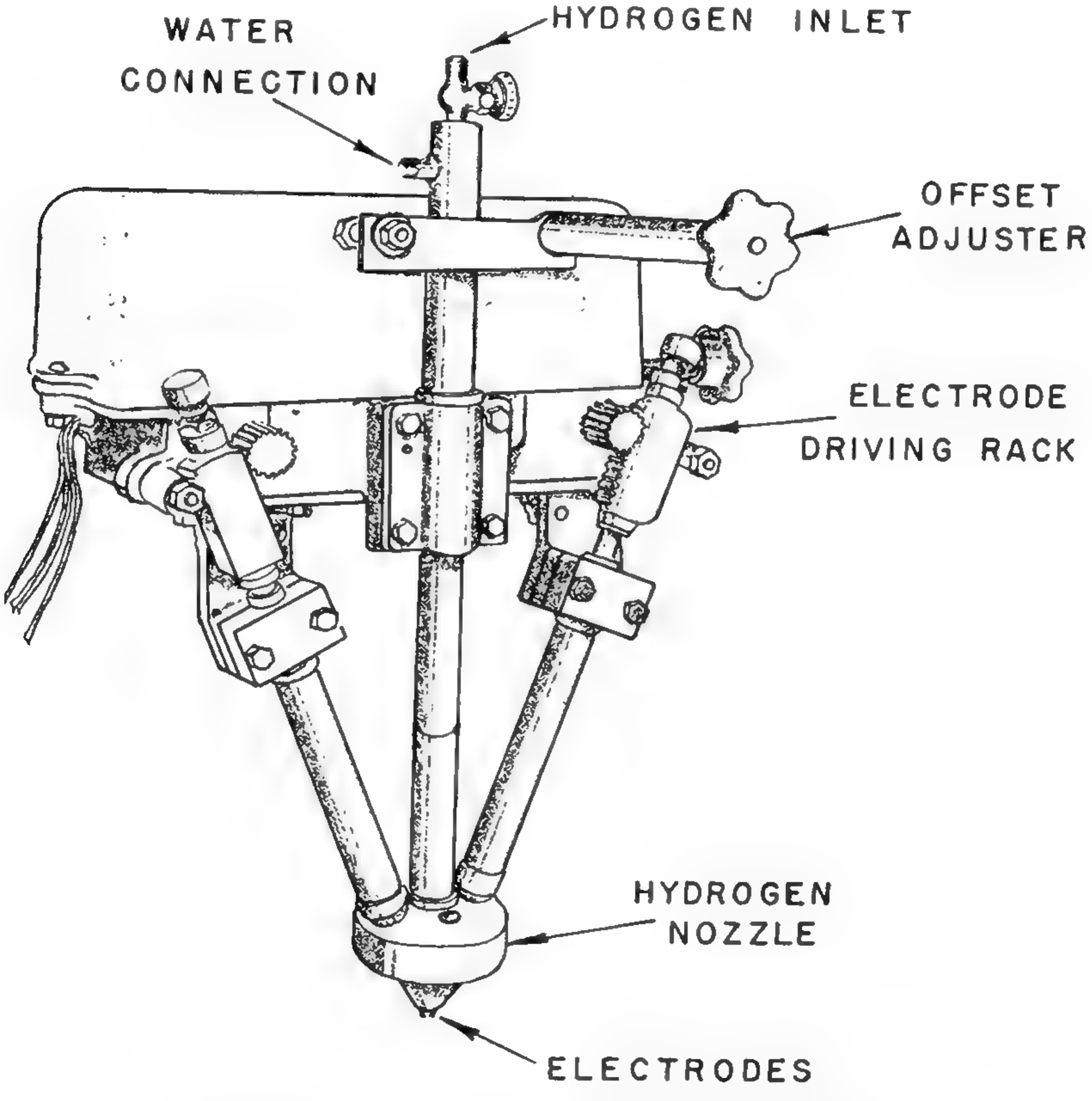

Fig. 27.—Automatic Atomic Hydrogen Welding Head

the work is approximately constant. Welding heads of this type are commonly controlled by thyratron tubes, utilizing the voltage regulation principles previously discussed. Because of the large amount of heat generated by the arc and the burning hydrogen in close proximity to the parts, the welding head is water cooled. Adjustment is provided for changing the position of the arc with respect to the electrodes by offsetting the electrodes.

Work Holding Fixtures

Accurate holding and adequate backing and chilling are essential to good machine welding economy. Particularly in welding thin sections, a very delicate balance is required between heat input rate and the rate of heat dissipation. If the input exceeds the dissipation, the work gets hotter as the welding progresses. The molten pool widens and deepens, and uniformity of welding is destroyed. Non-uniform chilling along the length of the

joint results in non-uniform welds. In manual welding, these variations can be compensated for by slight, usually unnoticed, changes in travel speed but in machine welding every effort is made to keep the heat input rate uniform and the dissipation must likewise be uniform.

This requirement dictates careful attention to several details in fixturing for machine welding:

1. Uniform backing and clamping pressure are essential. The thinner the work the more important this becomes. Thermal conductivity is largely influenced by the area of contact with the hot work. Multiple-spring pressure shoes may be required to achieve uniform clamping.
2. The location of clamping pressure must be controlled by relieving clamping members so that they will clear irregularities in the work and will always contact the work at a uniform distance from the joint.
3. Water cooling must frequently be used to prevent excessive heat build-up in the fixture and consequently decreased cooling as more and more welds are made.
4. Gas backing may be advantageous, especially in inert-gas metal-arc and atomic hydrogen arc welding. Helium or hydrogen may be used; both are good cooling gases.

In addition to the requirements for adequate chilling, fixtures should provide sufficiently strong clamping to prevent distortion of the work as it is heated by the arc. Fixtures themselves are sometimes distorted by heat, resulting in poor fit-up and trouble in welding.

Too often the economies that would otherwise be obtainable through mechanized welding are lost because of poor fixturing. Not infrequently the welding equipment or process is blamed for such losses when the root of the difficulty is actually inadequate holding and cooling of the parts.

H. MISCELLANEOUS ACCESSORIES

Welding Cables

Welding cables should be selected with attention to the level of welding current involved, the distance of the work from the machine, and whether a.c. or d.c. is used. Coverings of welding cables must be smooth and tough to enable them to be dragged easily and to resist punctures and abrasion by the continual abuse to which they are subjected.

For economical operation the cable sizes given in Table 9 should be used as these sizes will result in only a 4-volt drop in cables. Voltage drops in the cables mean power loss. In case of a 4-volt drop the power loss in the cables will amount to 10% of the output of the machine at 40 volts.

When welding with alternating current the effect of lead reactance is added to that of lead resistance resulting in greater reduction of welding current than when welding with direct current. Leads which are separated will result in further current reduction, therefore the welding leads should be closely spaced for welding with alternating current. Long leads do not affect the performance or loading on the transformer welding machine. To obtain the desired output at a distance, it may be necessary to set the welding machine for higher output.

At least 10 ft. of the electrode lead to which the electrode holder is attached should be the most flexible rubber-covered cable obtainable. This is an important factor in enabling the operator to manipulate his electrode readily and with less fatigue. The rest of the electrode lead and the work lead need not be extra flexible. The lengths of welding lead in general use are 25, 50 and 100 ft. and the sizes Nos. 2, 1, 0, 00 and 4/0. Cable splices should be carefully made, whether lugs and bolts or cable connectors are used. A loose cable connection causes overheating, and if it is subject to vibration it will interfere with the maintenance of a steady arc. The importance of using welding leads of ample current carrying capacity cannot be stressed too strongly. A 50-ft. lead of a given size may be ample to carry the required current, but should another 50-ft. length of the same size be added, the combined resistance of the two leads may drastically reduce the current output of the welding machine. When the machine is readjusted for the required output, in case of a motor-generator set, additional load will be placed on the drive motor, which results in added power consumption, and may overheat the motor.

Table 9— Recommended Sizes of Welding Leads (Electrode Holder and Ground)

Amps.	Distance in Feet from Welding Machine											
	50	75	100	125	150	175	200	225	250	300	350	400
100	2	2	2	2	1	1/0	1/0	2/0	2/0	3/0	4/0	4/0
150	2	2	1	1/0	2/0	3/0	3/0	4/0	4/0			
200	2	1	1/0	2/0	3/0	4/0	4/0					
250	2	1/0	2/0	3/0	4/0							
300	1	2/0	3/0	4/0								
350	1/0	2/0	4/0									
400	1/0	3/0	4/0									
450	2/0	3/0										
500	2/0	4/0										
550	3/0											
600	3/0											

Note: Based on direct current and 4-volt drop. Use next larger size for a.c. welding.

Electrode Holders

Electrode holders should be securely attached to the welding lead, should be properly balanced and, preferably be of the insulated type. The welder has a wide selection of holders to suit his individual taste. For trouble-free service the rated capacity of the holder should not be exceeded for prolonged periods.

Tools

The welder's personal tool kit should contain his steel identification stamp, fillet weld gages for welds $^3/_{16}$ to $^3/_8$ in., a machinist hammer, a spirit level, a plumb bob, square and flexible rule, several chisels, slag hammer and wire brush. The welder will find uses for a center punch, scriber and soapstone. All of these can be obtained readily, especially designed for the welder's use. The kit may be in the form of a carrier case, having separate compartments for electrodes and tools. A convenient tool for cleaning welds consists of a combination chipping hammer with chisel head and detachable wire brush. Well-equipped welding shops have light-weight pneumatic hammers for slag removal, peening and chipping. The use of safety goggles is important during these operations. While welding, the essential eye protector is a helmet or face shield in which a removable protective lens and cover glass of rectangular shape are inserted. (See Chapter 46 for further information on eye protection.)

Arc Time Measurement

Arc time recorders are used to provide accurate data for production control. These supply a check on the production by recording and totaling the time of actual welding. The instrument consists essentially of a relay system which energizes a time recorder when the arc is on. No time is recorded when the machine idles or when the electrode is grounded on the work-piece. Small-size control wires are employed together with the welding leads.

Some devices combine the above features with an automatic starter for the motor, thus the unit is shut off when welding is discontinued for a prolonged period, and can be started automatically when welding is resumed.

High-Frequency Pilot Circuits

The purpose of superimposing a high-frequency current on the welding circuit is to facilitate striking and maintaining the arc especially when low values of welding current are used. High-frequency equipment is available in self-contained units or built in with the welding transformer. The most widely used form consists of a spark-gap oscillator employing high voltage and high frequency in the order of 100,000 cycles. Capacitors are provided to bypass the transformer or generator coils and thus prevent the high-frequency current from passing through the power supply, thereby eliminating possible damage from this source. With the use of superimposed high-frequency current the electrode need not be touched to the work because the high-frequency current jumps the air gap and the welding current follows the ionized path thus established. The importance of this method in the starting of the arc is in the fact that in inert-gas welding the tungsten electrode need not come in contact with the work, eliminating possible contamination of the weld and possible burning through a light gage work-piece. (See also Section B of this Chapter.)

Crater Filler

The crater at the end of a weld deposited by arc welding does not present a good appearance and it may affect the strength of the joint. The presence of a crater in the joint is generally undesirable because it is likely to contain blow holes or cracks, even if the surface appears to be sound. Reducing the current at the end of a weld helps to fill craters by gradually decreasing the size of the molten pool.

Various kinds of equipment are used for this purpose, some motor-driven, some manually operated by a foot pedal. For d.c. welding generators the equipment is comparatively simple, consisting of a field rheostat which may be driven by a motor under the control of a switch, the electrode holder or operated by a foot pedal. In any case, the desired output during normal welding is set by the rheostat on the machine. Approximately 3 sec. are usually required for proper fading out of the arc. The welder maintains the same arc length as during welding.

With most a.c. welding machines, the equipment required for crater filling is more complicated and costly. Crater eliminators are not commonly used with a.c. welding machines, excepting some types of inert-gas metal-arc welding units

Welding Positioners

Welding positioners are used to position the work for welding in the flat position and help reduce welding time and cost. Positioners are operated by a crank, or in the case of large units by a motor. Some are designed to continuously rotate the work when the weld is of such a nature that it can be brought progressively into the most suitable position for the welder

BIBLIOGRAPHY

1. *Characteristics of Welding Arcs and Welding Set Circuits*, W. E. Stine, Journal of the American Society of Naval Engineers, February 1940.
2. *Electric Arc-Welding Machine and Electrode Standards*, Publication No. 45-105, National Electrical Manufacturers Association, 1945.
3. *D.C. Variable Voltage, Arc-Welding Sets*, 17W1c, U.S. Navy Dept., June 1945.
4. *D.C. Constant-Potential, Multiple-Operator, Motor-Generator Arc Welding Sets*, 17W5, U.S. Navy Dept., January 1946.
5. *Arc Starting Characteristics of D.C. Welders with Reference to Electrode Freezing*, J. M. Tryner, The Welding Journal, May 1946.
6. *A.C. Transformer-Type, Portable Arc-Welding Sets*, 17W6, U. S. Navy Dept., June 1946.
7. *Limited Input Arc Welders*, E. E. Steinert, The Welding Journal, September 1946.
8. *D.C., Variable-Voltage, Gasoline-Engine-Driven Arc-Welding Sets*, 17W8, U.S. Navy Dept., November 1946.
9. *National Electrical Code*, National Fire Protection Association, 1947.
10. *Power Supply for Inert-Arc Welding*, A. U. Welch, The Welding Journal, May 1948.

CHAPTER 9

CARBON-ELECTRODE ARC WELDING*

FUNDAMENTALS OF PROCESS

Definition and General Description

CARBON-ELECTRODE arc welding is a group of arc-welding processes wherein carbon electrodes are used, including shielded carbon-arc welding, inert-gas carbon-arc welding, carbon-arc welding and twin-carbon-arc welding.

Shielded Carbon-Arc Welding.—An arc-welding process wherein coalescence is produced by heating with an electric arc between a carbon electrode and the work. Shielding is obtained from the combustion of a solid material fed into the arc or from a blanket of flux on the work or both. Pressure may or may not be used and filler metal may or may not be used.

Inert-Gas Carbon-Arc Welding.—An arc-welding process wherein coalescence is produced by heating with an electric arc between a carbon electrode and the work. Shielding is obtained from an inert gas such as helium or argon. Pressure may or may not be used and filler metal may or may not be used.

Carbon-Arc Welding.—An arc-welding process wherein coalescence is produced by heating with an electric arc between a carbon electrode and the work and no shielding is used. Pressure may or may not be used and filler metal may or may not be used.

Twin-Carbon-Arc Welding.—An arc-welding process wherein coalescence is produced by heating with an electric arc maintained between two carbon electrodes and no shielding is used. Pressure is not used and filler metal may or may not be used.

Principles of Operation

Carbon-electrode arc welding is used both manually and automatically for welding ferrous and non-ferrous metals. The carbon arc is used only as a source of heat and does not serve as a medium for transferring metal as in shielded metal-arc welding. The burn-off rate of carbon electrodes is low and does not affect the weld to any appreciable extent. Extra weld metal, when needed for the joint, is obtained by introducing a welding rod into the heat of the arc and melting off the desired amount of metal.

In twin-carbon-arc welding the torch is used with the same techniques generally employed in gas welding. The twin-carbon torch is usually used where it is desired not to melt the base metals, as when brazing and soldering (see Chapters 22 and 23). With the twin-carbon-arc torch, a high temperature is maintained between two carbon electrodes clamped in adjustable jaws. The arc is played over the work much the same as a gas flame. Alternating current is generally used, although direct current, either polarity, may also be used.

Carbon-electrode arc welding has its widest use with automatic welding equipment in manufacturing items of uniform character that are made in relatively large quantities. Through automatic welding equipment electrically controlled, the arc voltage, arc current, arc travel speed and rate of feed of filler metal are all independently regulated. Direct current, straight polarity (electrode negative, work positive) is used. Provision is made for shielding the arc with a gas that is created by feeding a flux to the arc. Automatic equipment may also be used for carbon-arc welding without shielding.

General Effect of Process on Materials Welded

In carbon-electrode arc welding the application of heat and the filler metal feed are controlled separately. Thus in weld-

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* Prepared by a committee consisting of A. F. Davis, The Lincoln Electric Co., *Chairman;* R. H. Thoms, Truscon Steel Co.; R. F. Wyer, General Electric Co.

ing a thick piece to a thin piece, the heavier section can be heated sufficiently to melt it without adding any metal while so doing. With the carbon arc technique high heats are available for welding material which has high heat conductivity, such as copper.

With the carbon arc, welds can be made without adding any filler metal. This factor is important where no weld reinforcement is desired. In addition to the economy realized by not using filler metal, grinding and finishing operations can usually be eliminated. This technique is employed in making edge joints in thin gage sheet metal such as in the manufacture of tanks and other containers.

work does not form part of the electrical circuit, the metal is not melted. Only enough current is used to cause the welding rod to flow freely. The recommended current is between 50 and 75 amp. for $^5/_{16}$-in. rods. Whenever possible the joint should be welded in the flat position to secure best flow of molten welding rod. Best results are obtained when electrodes are held $^1/_4$ to $^3/_8$ in. away from the work.

Weld Quality

The assumption is often made that when welding steel with the carbon electrode, the carbon content of the weld metal is higher than that of the base

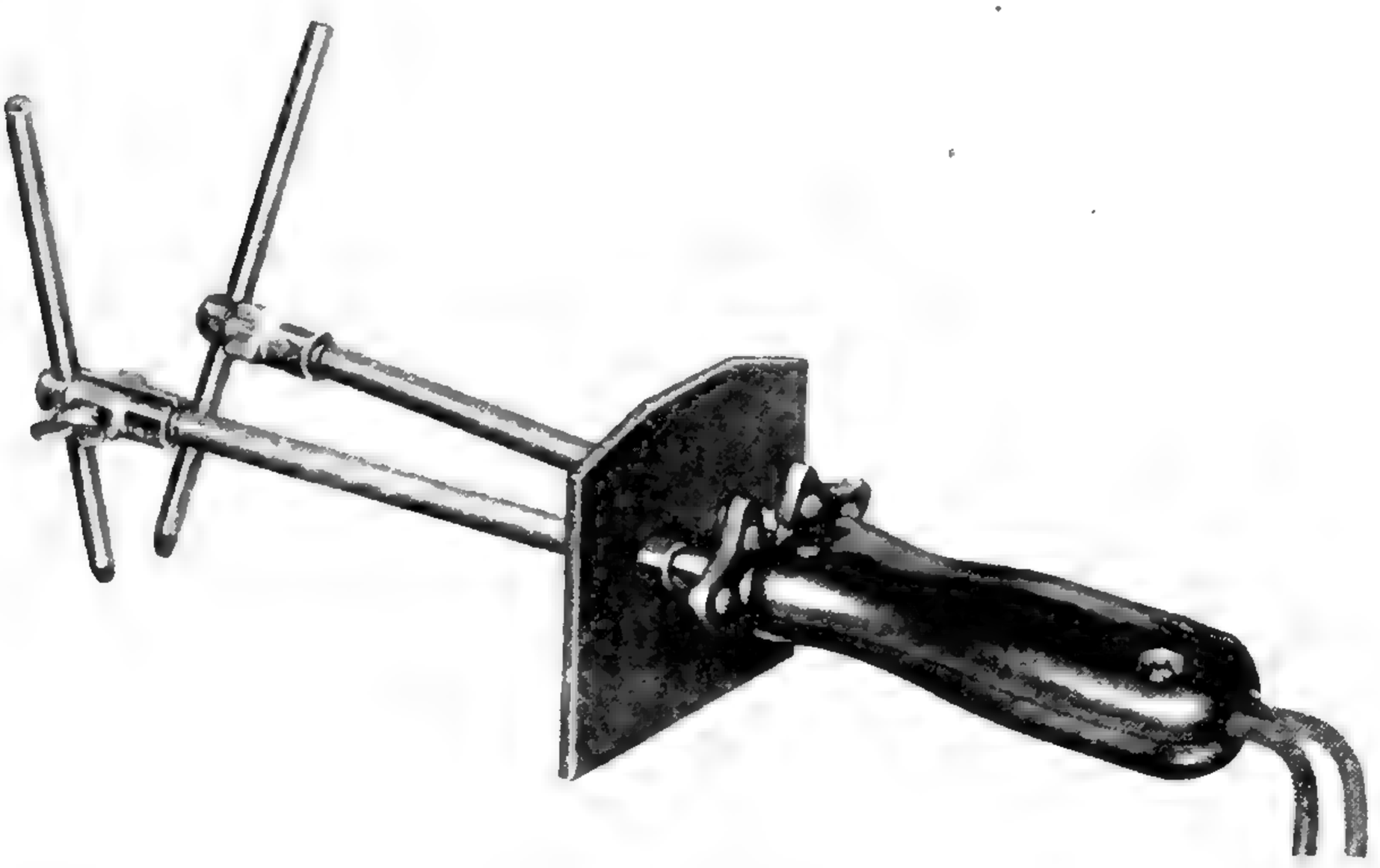

Fig. 1.—Twin-Carbon-Arc Welding Torch

With automatic equipment several other variations in technique are possible which affect the use of the process. Shielding of the molten metal is easier than for manual welding, thus giving a greater degree of control over the formation of oxides and vaporization. Also, the arc is controlled by superimposing a magnetic field around the carbon, and the effect of the arc can easily be changed from non-penetrating to gouging as the application requires. Warpage of the work is also reduced.

In twin-carbon-arc welding the same separate controls of heat and metal input are used somewhat differently. Since the

metal. This would be true only if the carbon actually contacted the molten metal, which of course is not the case. The following table gives carbon content of base metal and weld metal:

	Carbon Content, %	
Base Material	Weld Metal	Base Metal
0.07-0.12 (low)	0.06	0.10
0.15-0.25 (medium)	0.11	0.20
0.30-0.40 (high)	0.15	0.32

The properties of welds made with the carbon arc in mild steel vary little from those of welds made with the metal arc. Since the carbon arc can be shielded, these properties are therefore nearly the

same as those made with covered metal electrodes.

In welding non-ferrous metals, welds of high tensile strength and ductility are produced when recommended procedures are followed and the base metal falls within the ranges of those normally classed as weldable.

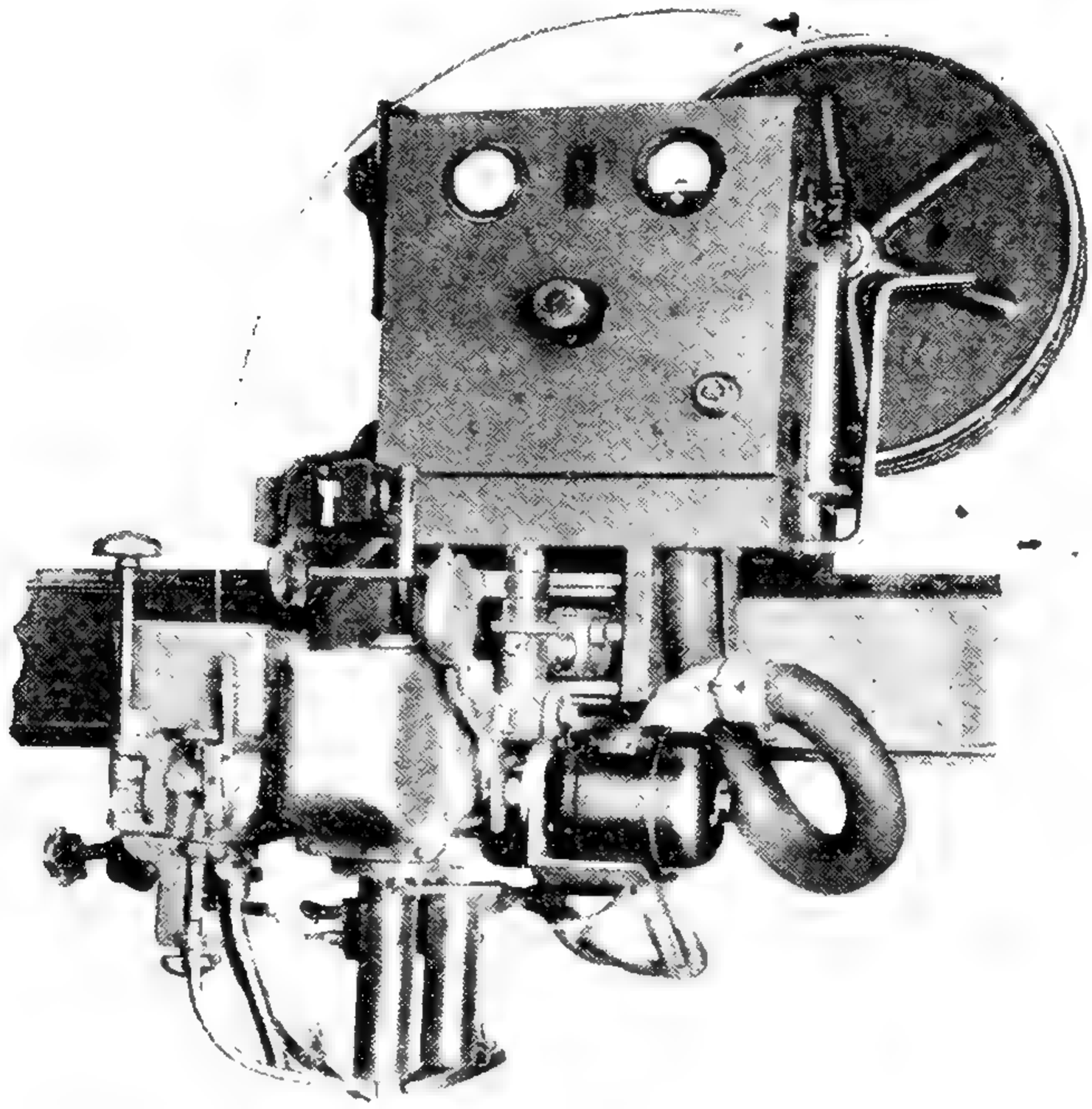

Fig. 2.—Automatic Carbon-Arc Welding Head

EQUIPMENT USED

Machines

For manual carbon-arc welding no special equipment is needed. Carbons range in size from $^{5}/_{32}$ to $^{1}/_{2}$ inch. When using the larger sizes on fairly continuous operations, a special water-cooled holder will increase operator comfort and efficiency. Adapters for holding large carbons in regular electrode holders are available as well as special, air-cooled holders.

The twin-carbon arc torch (Fig. 1) has two adjustable arms in which are clamped the carbon electrodes. The arms are usually geared so that adjustment can be made while operating the torch to maintain a constant distance between the electrodes as they are slowly consumed. The torch operates at 35 to 40 volts and since the majority of arc-welding controls are calibrated in amperes at the average metal arc of 25 to 30 volts, the machine controls should be set 20% above recommended current settings. Copper-coated and cored carbons are generally used from $^{3}/_{16}$ to $^{5}/_{8}$ in. in diameter.

For automatic carbon-arc welding a d.c. generator of the variable voltage type is required to supply welding current and power to drive the head.

The welding head is a motor-driven mechanism for holding and feeding the carbon electrode. In some applications the head is mounted on a carriage and travels on a beam, welding the seam while the work remains stationary under it. This requires a fixture for holding the work and a power-driven fixture for moving the welding head. A typical head is shown in Fig. 2.

In other applications the welding head

remains stationary while the work moves under the carbon arc. The welding head is mounted at the proper distance from the work which is moved by the fixture along under the arc. In a third type of application the welding head is mounted on a self-propelled tractor which travels along the seam.

The head automatically strikes the arc and feeds the carbon through a water-cooled *magnetic boot*. The carbon is also revolved during the welding to maintain a uniformly pointed tip and to self clean the bushing where the current contact is made. The exposed portion of the electrode is kept relatively short, $1^1/_2$ to 2 in., to permit the use of greater current densities for a given diameter than for manual welding. Also, the life of the electrodes is much longer than the life of electrodes for manual welding due to the lesser surface exposed to oxidation below the contact. Most carbons used for automatic welding are of the coke rather than the graphitic type as there is no advantage in using the latter since comparatively small area is exposed to oxidation. The length of electrodes varies from 12 to 36 inches.

The carbon arc is very easily affected by magnetic fields set up by the welding current and the distribution of magnetic material in the particular piece being welded. In order to stabilize and focus the arc in a desired direction, a separate magnetic field is used. This magnetic field is generally built into or around the welding boot through which the carbon feeds. The three types of control most generally used are: (1) the alternating-current boot; (2) the direct-current boot; (3) the twin boot. The effects of magnetic fields on the carbon arc can be noted in Figs. 3 and 4. These effects are lessened as the height of the boot above the work is increased.

The alternating-current boot is one in which the field is produced by a shunt coil generally energized by a 110-volt supply. It is used for welding light-gage material and also where base metal is unsymmetrical above the seam.

The direct-current boot is energized from the welding current. It is used for welding butt and lap joints in medium gage material. The penetration for a given welding current and speed is about 20% greater than for the alternating-current boot and the width of the weld is about 20% less.

The twin boot, which is shown in Fig. 2, consists of a welding boot and a magnetic boot with adjustable pole piece. These boots are connected in series and are energized by the welding current. They are arranged to produce a backward blow of the arc so that the force of the arc tends to propel the molten metal away from the carbon toward the point of solidification. The twin boot is used with powdered fluxes in making butt welds in material $^1/_4$ in. and heavier.

Shielding Fluxes

The protection of the molten metal from the atmosphere is accomplished by gas- and slag-forming fluxes introduced into the arc by means of an automatic feeding mechanism attached to the welding head.

Three types of flux are used: paste type for light slag forming; fibrous type in the form of chemically impregnated paper cord; and powder type for heavy slag forming.

The light slag-forming fluxes are mixed with water and brushed on the seam prior to welding. Several kinds are used, each being designed to suit the chemical analysis range of base materials or type of joint. They are used when

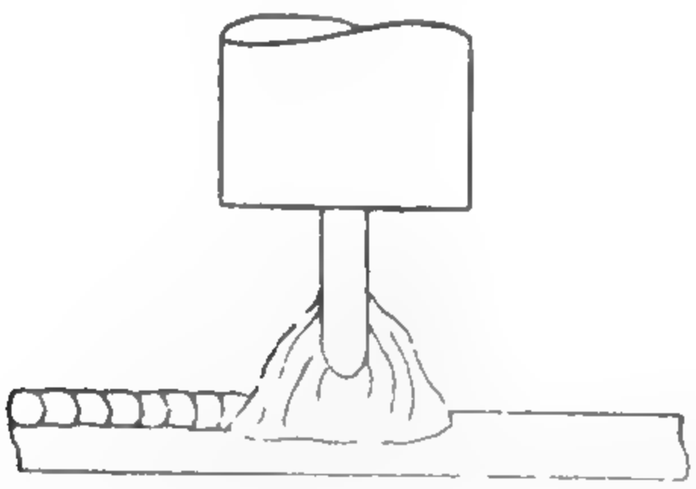

Fig. 3.—Carbon-Arc Without Magnetic Field

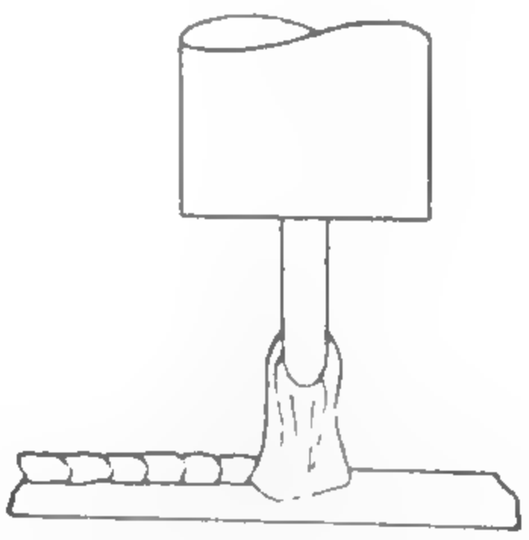

Fig. 4—Carbon-Arc with Superimposed Magnetic Field

welding voltages are from 19 to 25 volts.

The paper cord flux produces a gaseous shield which protects the metal from oxidation. It also performs the function of stabilizing the arc. This type of flux is used in welding steel having a thickness range of 16 gage to $^5/_{16}$ inch. Paste type fluxes may be used with fibrous fluxes. Figure 5 is a diagrammatic sketch showing fibrous cord being fed into the arc.

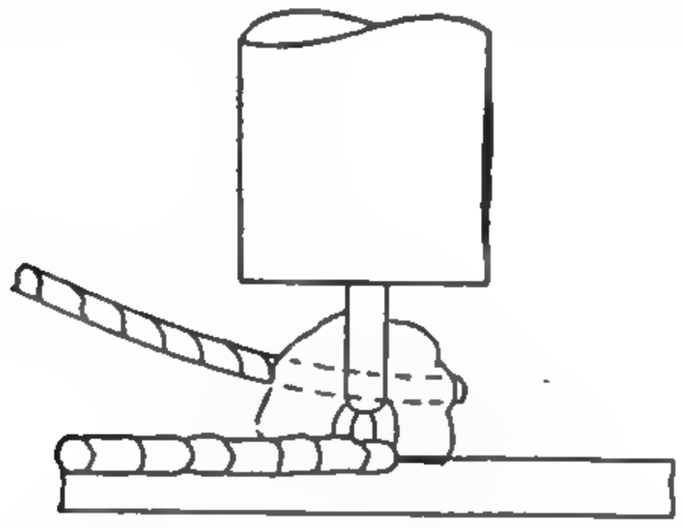

Fig. 5.—Shielding by Means of Fibrous Paper Cord

Powdered fluxes are used for steel plates $^1/_4$ in. thick and heavier where the amount of molten metal exposed to the atmosphere is greater than for thinner material. They produce a layer of heavy slag over the bead. Special powdered fluxes are also used for welding aluminum and stainless steel. The powder flux feeder is shown in Fig. 2.

COMMON APPLICATIONS

General

The carbon electrode is used for arc-welding steel, cast iron, galvanized steel, copper, brass, bronze and aluminum. The carbon-arc is also used to advantage as a cutting tool and, with the twin-arc torch, it is used for brazing and soldering both light and heavy copper, galvanized and tinned parts. The carbon-arc is also used for preheating small areas prior to welding and for applying heat for bending and straightening operations.

Steel

For the manual welding of steel with the carbon electrode the following electrode sizes and maximum currents are characteristic:

Diameter of Carbon Electrode, In.	Maximum Current, Amp.
$^5/_{32}$	50
$^3/_{16}$	100
$^1/_4$	200
$^5/_{16}$	350
$^3/_8$	450
$^1/_2$	700

Smaller currents may be used, depending on the weight or thickness of the base metal.

The electrode should be tapered from where it is gripped in the holder to a tip approximately half the diameter of the electrode. Straight polarity, electrode negative, is used in almost all cases.

The principal use of manual carbon-arc welding in steel is in making edge joints without addition of filler metal. This is done chiefly in thin gage sheet metal work, such as tanks, where the edges of the work are fitted closely and simply fused together. Table 1 gives average conditions for making such edge joints.

Table 1 — Edge Joints in Steel (Manual)

Metal Thickness, Ga.	Voltage	Current, Amp.	Electrode Size, In.	Welding Speed, Ft./Hr.
16	25	90–100	$^3/_{16}$	135
14	25	125–135	$^1/_4$	125
12	25	200–250	$^1/_4$–$^5/_{16}$	110
10	25	250–275	$^1/_4$–$^5/_{16}$	100

For welding heavier gage plates and for applications where the work presents a large volume of uniform pieces, automatic carbon-arc welding is generally used. A comparison between the automatic and manual procedures, of the electrode diameters and the respective currents used will indicate the cost-reducing, higher welding speeds that can be realized with automatic equipment.

The following electrode sizes and current ranges are characteristic for automatic carbon-arc welding of steel:

Diameter of Carbon Electrode, In.	Current Range, Amp.
$^1/_4$	50–350
$^5/_{16}$	100–700
$^3/_8$	150–900
$^1/_2$	200–1100
$^5/_8$	250–1400

Because of the higher amperage used the rate of travel of the arc is increased greatly, thus reducing overall welding time.

Tables 2 to 10 give welding data for automatic welding of various types of joints in steel. The information includes metal thickness, currents, voltages and welding speeds together with the type of flux and, where necessary, the amount of filler metal required.

The data shown in these tables are ap-

proximate and should be varied as necessary for any application depending on variations in such factors as steel quality, uniformity and closeness of fit-up, surface condition of steel, desired amount of weld reinforcement and the use of jigs and fixtures. Any one of the factors shown in the table, whether voltage, current, speed, type of flux or reinforcement, may be changed independently of the other factors to meet specific requirements.

Fig. 6.—Automatic Welding of Butt Joints Using Filler Metal and a Copper Backing (Table 2)

The data shown in these tables are for making straight lengths of butt, edge, lap and corner joints in mild steel within the range as indicated below:

Carbon	0.15 to 0.25%
Manganese	0.35 to 0.60%
Silicon	0.07% max.
Sulfur	0.05% max.
Phosphorus	0.045% max.

Travel speeds will be slower for steels outside this range.

Fig 7.—Automatic Welding of Butt Joints Without Filler Metal or Backing (Table 3)

Table 2 gives data for making butt joints in tanks, range boilers, pipe and similar products, and made with the work clamped in position on a copper backing. For this type of joint the filler metal is automatically fed into the arc and both paste and fibrous flux together are used. (See Fig. 6.)

Fig. 8.—Automatic Welding of Butt Joints Without Filler Metal or Backing (Table 3)

Table 3 gives data for making butt joints without root opening and without filler metal securing 70% penetration. Seams are clamped tightly together as shown in Figs. 7 and 8. This type of joint is used for automobile axle housings, motor and generator frames, ship channels and other similar products.

If the steel conforms closely to the steel previously recommended for good welding quality the current recommended for 14 ga. to $^{3}/_{16}$ in., inclusive, may be increased to 450 amp. with a corresponding increase in welding speed.

Table 4 gives data for making butt joints without root opening and with filler metal. This type of joint (Fig. 9) is stronger than a joint made without filler metal and will have 70% penetration. It is used on torque tubes, railroad

Fig. 9.—Automatic Welding of Butt Joints Using Filler Metal But No Backing (Table 4)

car center sills, etc.

Table 5 gives data for making butt joints with 100% penetration by welding from both sides (see Fig. 10). Welding rods may be tacked onto the seam, but filler metal fed automatically into the arc is recommended. Some applications permit applying the filler metal on only one side of the seam.

Fig. 10.—Automatic Welding of Butt Joints Using Filler Metal and Welding from Both Sides (Tables 5 and 9)

The above data may be used for welding high-tensile steel in which case the high side of the current and voltage ranges are to be used. When an angle is specified it indicates the degree of tilt at the point of welding so the welding will progress up an incline.

Table 6 gives data for making lap joints of the type shown in Fig. 11 which

Fig. 11.—Automatic Welding of Lap Joints Without Filler Metal (Table 6)

are used in making mufflers, tanks, range boilers and ships. No filler metal is required and the work is clamped or tacked in position.

Where the steel conforms closely to the steel previously recommended for good welding quality, the above currents may be increased about 75 amp. with a corre-

Table 2 — Butt Joints Using Filler Metal and Copper Backing

Metal Thickness	Voltage	Current, Amp.	Electrode Diameter, In.	Flux	Filler Metal Lb./Hr.	Welding Speed, Ft./Hr.
16 ga.	42	180	5/16	Fibrous + paste	5	160
14 ga.	42	240	5/16	Fibrous + paste	5	160
12 ga.	42	300	5/16	Fibrous + paste	5	140
10 ga.	42	375	5/16	Fibrous + paste	5	100
3/16 in.	38	375	3/8	Fibrous + paste	5	75
1/4 in.	38	400	3/8	Fibrous + paste	5	60
5/16 in.	38	450	3/8	Fibrous + paste	5	45

Table 3 — Butt Joints With No Filler Metal and No Backing

Metal Thickness	Voltage	Current, Amp.	Electrode Diameter, In.	Flux	Welding Speed, Ft./Hr.
16 ga.	22	200	5/16	Paste	300
14 ga.	24	250	5/16	Paste	300
12 ga.	24	350	5/16	Paste	260
10 ga.	24	375	5/16	Paste	180
3/16 in.	35	400	3/8	Fibrous + paste	150
1/4 in.	38	450	3/8	Fibrous + paste	120
5/16 in.	38	450	3/8	Fibrous + paste	100
3/8 in.	38	450	3/8	Fibrous + paste	75

Table 4 — Butt Joints With Filler Metal and No Backing

Metal Thickness	Voltage	Current, Amp.	Electrode Diameter, In.	Flux	Filler Metal Lb./Hr.	Welding Speed, Ft./Hr.
14 ga.	42	160	5/16	Paste	3	260
12 ga.	42	200	5/16	Paste	3	200
10 ga.	42	290	5/16	Paste	3	160
3/16 in.	38	375	3/8	Fibrous + paste	5	140
1/4 in.	38	450	3/8	Fibrous + paste	5	110
5/16 in.	38	450	3/8	Fibrous + paste	5	90
3/8 in.	38	450	3/8	Fibrous + paste	5	65

Table 5 — Butt Joints Welded From Both Sides With Filler Metal

Metal Thickness, In.	Voltage	Current, Amp.	Electrode Diameter, In.	Flux	Filler Metal, Lb./Hr.	Angle, Deg.	Welding Speed, Ft./Hr.
1/4	29–34	700	1/2	Powder	9.0	0	50
3/8	30–35	750	1/2	Powder	9.0	0	50
1/2	30–35	750	1/2	Powder	8.5	3	42.5
5/8	31–36	750	1/2	Powder	7.5	3	35.0
3/4	32–37	700–750	1/2	Powder	6.5	6	22.5
7/8	32–37	750–800	1/2	Powder	6.5	6	17.5
1	32–37	800–850	1/2	Powder	6.5	6	15.0

Table 6 — Lap Joints Without Filler Metal

Metal Thickness	Voltage	Current, Amp.	Electrode Diameter, In.	Flux	Welding Speed, Ft./Hr.
18 ga.	25	225	5/16	Paste	150
16 ga.	25	250	5/16	Paste	135
14 ga.	26	325	5/16	Paste	125
12 ga.	30	325	5/16	Fibrous + paste	110
10 ga,	32	325	5/16	Fibrous + paste	100
3/16 in	33	325	3/8	Fibrous + paste	90
1/4 in.	33	350	3/8	Fibrous + paste	70
5/16 in.	35	400	3/8	Fibrous + paste	50
3/8 in.	35	400	3/8	Fibrous + paste	40

NOTE: If joint is tilted about 5 degrees speeds may be increased as much as 50%.

sponding increase in the welding speed.

Table 7 gives data for making edge joints as illustrated in Fig. 12. Typical applications include mufflers, tanks, compressor housings and similar parts.

Fig. 12.—Automatic Welding of Edge Joints Without Filler Metal (Table 7)

Table 8 gives data for making corner joints. The work should be clamped in place on a copper backing where 100% penetration is required. In cases where less penetration is required the backing may be omitted. No filler metal is required (see Fig. 13). Square tanks and street lighting standards are typical examples of the use of this type of joint.

Welding for approval under the ASME Code for Unfired Pressure Vessels, Par. U-68 or U-69, requires variation in the above procedures. Data shown are for steel with the following analysis:

Carbon	0.10 to 0.35%
Manganese	0.90% max.
Silicon	0.20% max.
Phosphorus	0.04% max.
Sulfur	0.05% max.

Some steels having analyses outside the above range can be welded satisfactorily using the data shown. However, it may be necessary to use lower speeds and welding currents to obtain satisfactory results. On the other hand steels of unusually good welding quality may be welded at higher speeds.

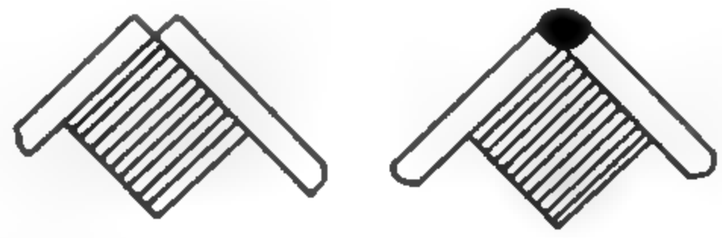

Fig. 13.—Automatic Welding of Corner Joints Without Filler Metal. A Backing Is Used Where 100% Penetration Is Required (Table 8)

The data shown in Table 9 will give 100% penetration on straight seams, welded from both sides using filler metal and powdered flux (see Fig. 10).

The data in Table 10 will give 50% penetration for joints welded using a backing weld and adding filler metal.

Galvanized Steel

Galvanized steel may be welded manually with the carbon-arc. If the recommended welding procedure is followed the carbon-arc has a negligible effect on the

Table 7 — Edge Joints Without Filler Metal

Metal Thickness	Voltage	Current, Amp.	Electrode Diameter, In	Flux	Welding Speed, Ft./Hr.
20 ga.	22	120	1/4	Paste	250
18 ga.	22	120	1/4	Paste	225
16 ga.	25	120	1/4	Paste	200
14 ga.	25	140	5/16	Paste	185
12 ga.	25	275	5/16	Paste	170
10 ga	25	325	5/16	Paste	150
3/16 in.	25	350	5/16	Paste	140
1/4 in	25	350	5/16	Paste	135

Table 8 — Corner Joints Without Filler Metal

Metal Thickness	Voltage	Current, Amp.	Electrode Diameter, In.	Flux	Welding Speed, Ft./Hr.
18 ga	24	120	1/4	Paste	130
16 ga.	24	135	1/4	Paste	130
14 ga	24	150	1/4	Paste	130
12 ga.	25	275	5/16	Paste	115
10 ga	32	325	5/16	Fibrous + paste	100
3/16 in.	32	350	5/16	Fibrous + paste	90

Table 9 — Butt Joints Welded From Both Sides

Metal Thickness, In	Voltage	Current, Amp	Electrode Diameter, In.	Flux	Filler Metal, Lb./Hr.	Angle, Deg.	Welding Speed, Ft./Hr.
1/4	29-34	650	1/2	Powder	8.0	0	42.5
1/4	30-35	650	1/2	Powder	8.0	1 1/2	32.5
1/2	30-34	600	1/2	Powder	6.5	3	32.5
3/4	31-36	750	1/2	Powder	6.5	3	17.5
3/4	32-37	700	1/2	Powder	6.5	6	15.0

Table 10 — Butt Joints Using A Backing Weld

Metal Thickness, In.	Voltage	Current, Amp.	Electrode Diameter, In.	Flux	Filler Metal, Lb./Hr.	Angle, Deg.	Welding Speed, Ft./Hr.
1/4	29-34	650	1/2	Powder	8.0	0	85
3/8	30-35	650	1/2	Powder	8.0	1 1/2	65
1/2	30–35	600	1/2	Powder	6.5	3	45
5/8	31–36	750	1/2	Powder	6.5	3	35
3/4	32–37	700	1/2	Powder	6.5	6	35

corrosion-resistant qualities of the material. Although the heat-affected zone may appear to have lost its zinc coating, the coating has actually only been melted and not burned off. Even a zone which appears to have lost all zinc still resists corrosion better than ungalvanized steel.

The following procedure is suitable for welding galvanized sheets from 16 to 22 gage inclusive, using a copper-silicon-manganese welding rod.

For 16 and 18 ga., a 3/32-in. diam. welding rod and a 5/32-in. carbon electrode are used. For 20 and 22 ga., a 1/16-in. diam. welding rod and a 5/32-in. carbon electrode are used.

Carbon electrodes for welding galvanized steel should have a long thin taper. A standard 5/32-in. diam. carbon electrode should be ground down with a gradual taper to a very small point. This is held in the electrode holder about 1 1/2 in. from the point so that during welding it will remain necked down and tapered.

The current should range from 50 amp. for 16 ga. down to 20 amp. for the lighter gages, depending on the type of joint being made. The arc should always be played on the welding rod and not on the galvanized sheet, and should be as short as can be maintained. If the proper current and arc length are used, smooth welds will result. The welding of galvanized steel smoke stacks is shown in Fig. 14.

Cast Iron

Iron castings may be welded manually with the carbon-arc using a cast-iron welding rod. A machinable weld can be made in the flat position on heavy castings by proper manipulation of the arc and welding rod. Cooling of both deposited and base metal can be retarded by playing the arc upon the work. The hard spots that complicate machining can be largely eliminated by using dehydrated borax flux and floating the oxides out of the molten metal.

The cast-iron welding rod used with the carbon electrode is usually of far higher grade material than the base metal. The tensile strength of the weld metal will therefore normally be higher than that of the casting.

Copper

Copper may be welded by carbon-arc welding either manually or automatically. Where economically feasible, automatic welding is recommended for best results, namely a smooth, dense weld.

For manual carbon-arc welding of copper, it is important to maintain uniform welding current and voltage.

The composition of the welding rod will vary according to the physical and mechanical characteristics required of the welded structure. If the weld must have low electrical resistance, the filler metal may be of pure copper. Where electrical or thermal conductivity are not essential but ductility and strength are required, the filler metal may be copper silicon or a suitable grade of phosphor bronze.

The joint must be clean for welding. A 10% solution of sulfuric acid is effective if oxides are present. Thicknesses up to 1/4 in. need not be beveled, but for greater thicknesses beveling as previously recommended for steel should be followed. Welding is greatly facilitated when the work is clamped to a backing of carbon or graphite blocks. If this is not practical, the two sheets may be elevated on a piece of metal about the thickness of a hack-saw blade so that there is clearance between the bottom of the joint and the work table. This permits a small amount of weld metal to come through to the underside, giving a flush joint on that side.

There should be a 1/8-in. root opening. The welding rod should be about 20% larger in diameter than the thickness of the metal being welded. Best results are obtained at high speeds, always directing the arc on the welding rod. For example,

better welds will be made at 20 in. per min. with 600 amp. than at 7 in. per min. at 200 amperes.

The arc should be long and the voltage high. The distance between the carbon electrode and the work should be such as to allow the carbon monoxide produced by the arc to combine with the atmosphere rather than with the copper to form an oxide. The weld should be made in one pass.

Due to the high heat conductivity of copper, preheating may be necessary when lower currents are used. This can be done by moving the carbon arc rapidly over the surface.

With automatic welding, the material is clamped on a grooved carbon or copper backing strip. For making butt welds in material 16 gage to $^{3}/_{16}$ in. thick, this groove should be $^{1}/_{32}$ in. deep by $^{3}/_{8}$ in. wide; with heavier material, the depth of the groove should be increased to $^{1}/_{16}$ inch. When it is essential that the weld metal be copper, a deoxidized-copper welding rod is used to furnish the desired reinforcement; otherwise phosphor bronze or silicon bronze alloys are used because of their free-flowing characteristics. No flux is used, the joint being kept free of foreign material and moisture. The welding techniques and speed are comparable to those given for mild steel except that the voltages should be increased to 35 or 45 volts depending on the thickness of the material, the higher voltages being used for the thicker gages. When welding $^{1}/_{4}$ in. thick and heavier material, it is necessary to preheat if the mass of the material is such that the heat from welding otherwise would be conducted away too rapidly.

One of the extensive uses of the carbon-arc with automatic equipment is for

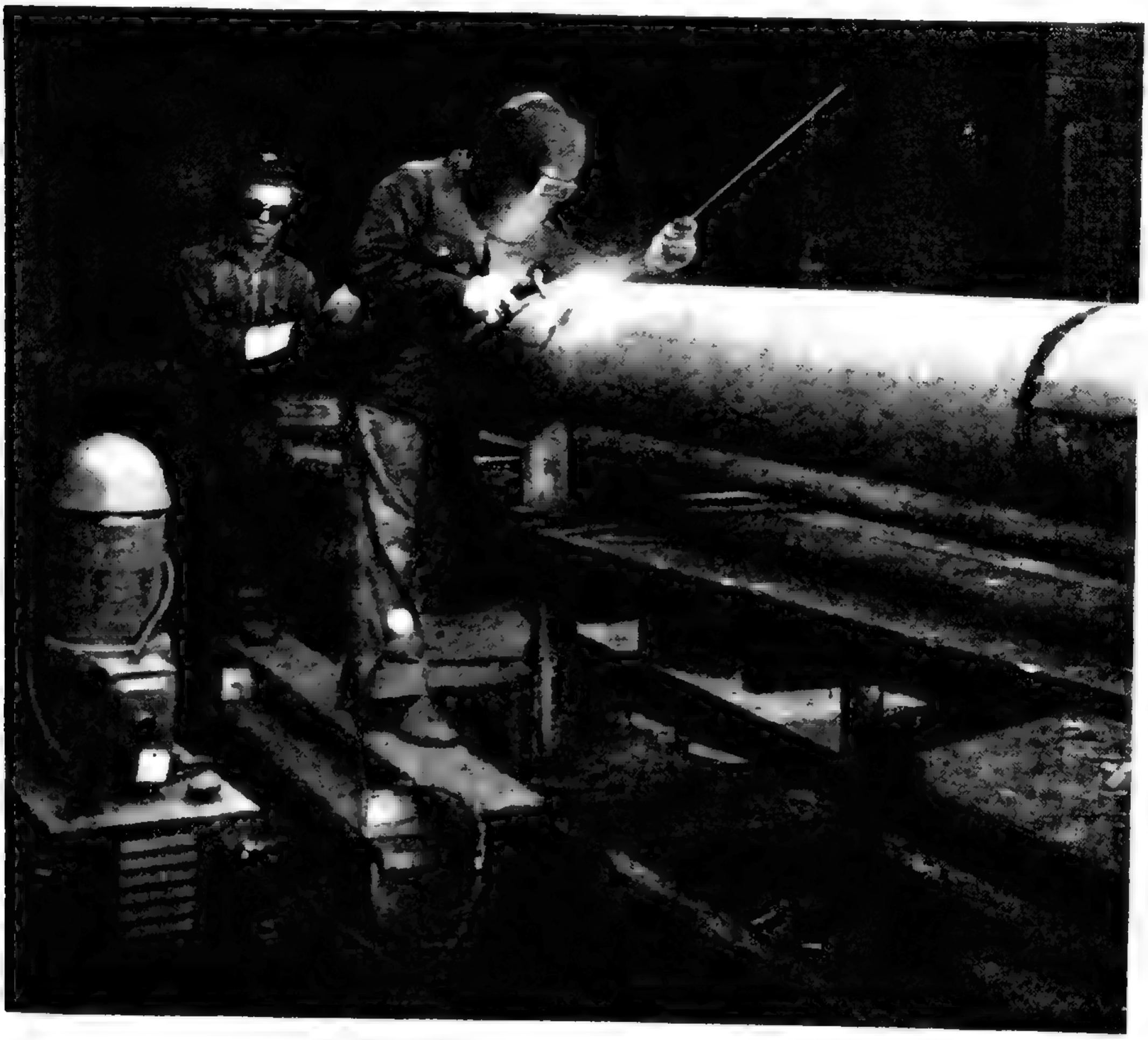

Fig. 14.—Welding Galvanized Smoke Stack

welding the end rings and bars on small fractional horsepower motor rotors. Figure 15 illustrates this application. In this type of work, automatic welding as compared with manual welding has increased production speeds by as much as 50% while increasing the power output of the motor by 20%. Welding speeds range from 18 to 36 in. per min., depending on the cross-section of the rotor ring, with the current generally around 100 amperes.

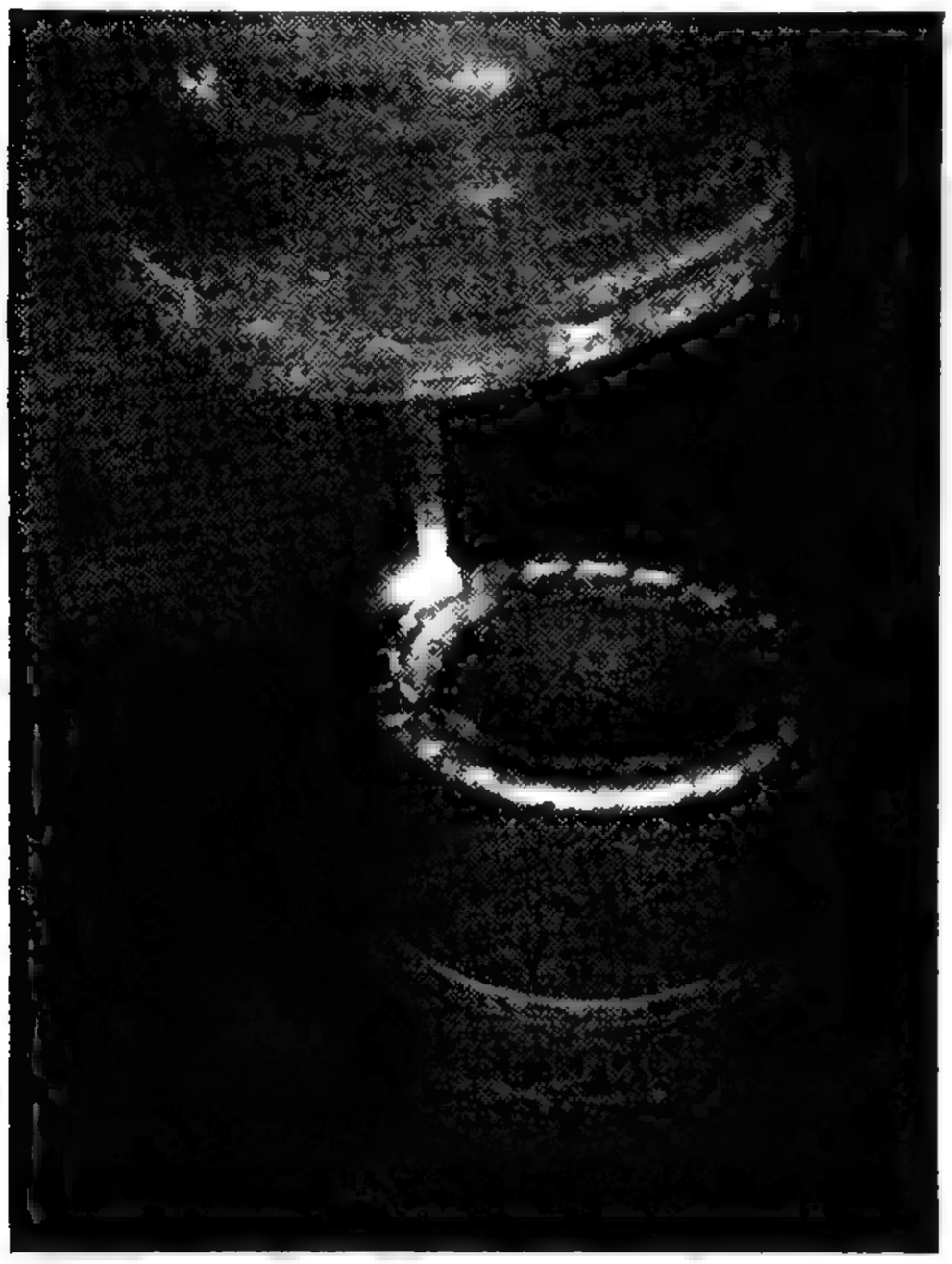

Fig. 15.—Welding Copper End Rings on Motor Rotor

A small rotor can be welded in approximately 15 seconds. Preheating to from 400 to 700° F. is advisable, although not always necessary. Automatic welding has made it possible to greatly simplify the manufacture of rotors.

Procedures for welding silicon bronzes vary only slightly from those used in welding copper. For butt welding side seams of water tanks (Fig. 16), the material is clamped in a fixture against a grooved copper backing, the groove being $^{1}/_{32}$ in. deep by $^{3}/_{16}$ in. wide. The edges and top and bottom surfaces in the weld zone must be absolutely clean of any scale or foreign material.

A flux composed of 90% fused borax and 10% sodium fluoride mixed with methyl alcohol is painted on the seam prior to welding or may be sprinkled lightly on the joint in powered form. Table 11 gives data for welding copper alloys.

Aluminum and Its Alloys

Automatic carbon-arc welding may be used economically for welding aluminum and its alloys where the volume of production is large and where pieces to be welded are uniform in shape. Welds are of high quality with respect to uniformity, appearance and physical properties.

Because of the high current densities used and the fast travel speeds, no scarfing or preheating of the base metal is necessary in thicknesses from 14 ga. to $^{3}/_{4}$ inch. Welds can be made in a single pass and the amount of filler metal used can be controlled independently of the carbon electrode. Thus weld reinforcement is kept to a minimum.

Successful carbon-arc welding in aluminum depends to a large extent on the use of weldable alloys. The following are the aluminum alloys most commonly carbon-arc welded: 2S, 3S, 14S, 24S, 52S, 53S and 61S. (See Chapter 32 for analyses.)

All joints to be welded should be clean and dry with edges butted tightly without root opening for uniform results. Root openings up to $^{1}/_{32}$ in. are permissible, but, in general, should not be more than 10% of the metal thickness. Tack welding prior to final welding is suggested in material $^{3}/_{8}$ in. or thicker. The tack welds must be flat so high currents should be used. End tabs should be

Table 11 — Butt Joints For Copper Alloys

Metal Thickness, In.	Voltage	Current, Amp.	Electrode Diameter, In.	Welding Rod Diameter, In.	Welding Speed, In./Min.
$^{1}/_{16}$	24	130	$^{1}/_{4}$	$^{3}/_{32}$	24
$^{3}/_{32}$	24	150	$^{1}/_{4}$	$^{3}/_{32}$	20
$^{1}/_{8}$	25	170	$^{1}/_{4}$	$^{1}/_{8}$	18
$^{5}/_{32}$	25	200	$^{1}/_{4}$	$^{1}/_{8}$	16
$^{3}/_{16}$	25	225	$^{1}/_{4}$	$^{1}/_{8}$	14

tacked in place at the ends of the seams for starting and finishing the welds. A backing strip must be used to secure 100% penetration, welding from one side only in material up to and including 3/4 inch. Copper is the best material for such backing. The backing strip should be grooved, the depth and width of the groove varying with the metal thickness (see Table 12 for proper groove size).

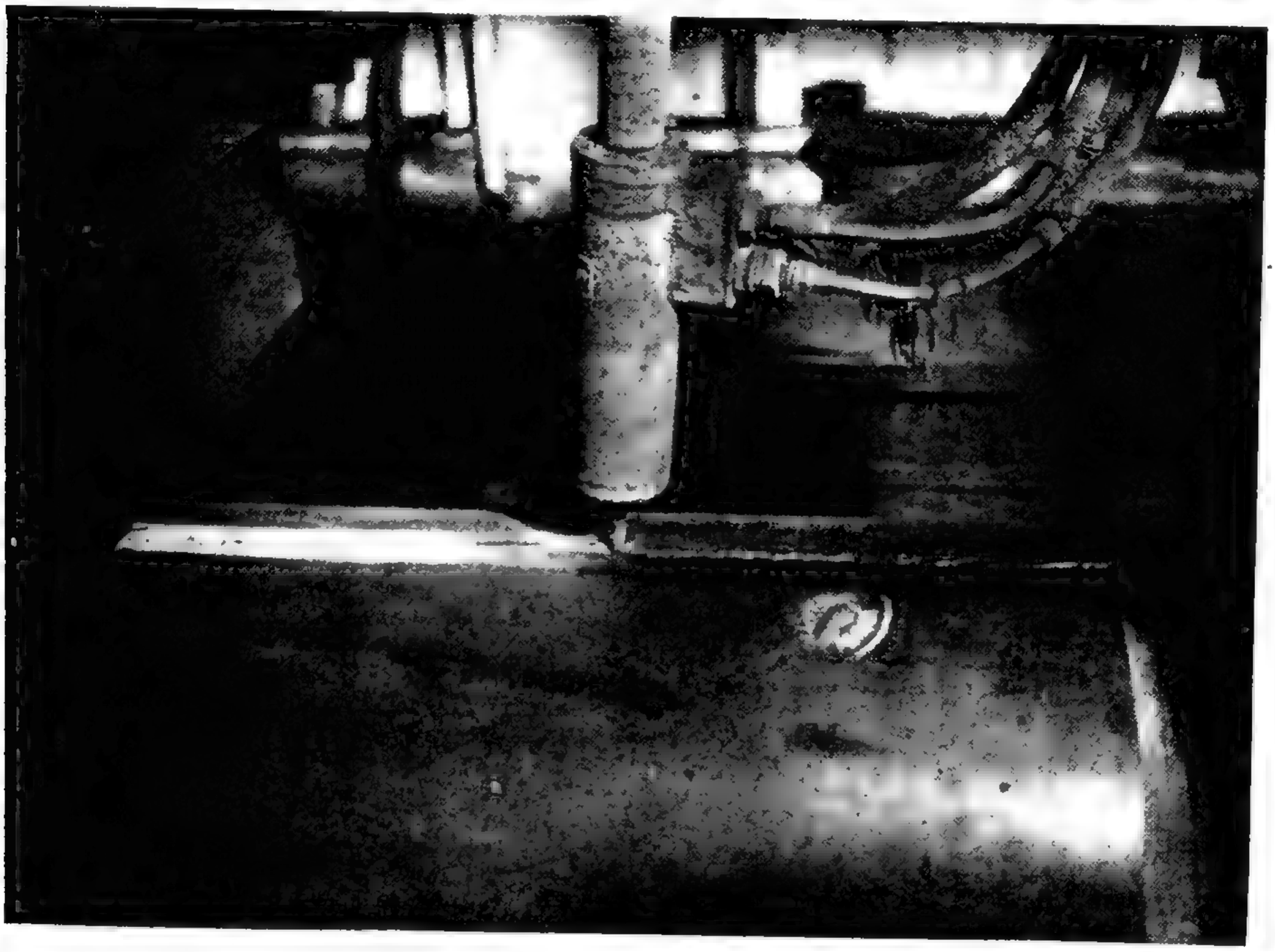

Fig. 16.—Welding Longitudinal Seams of Copper Hot Water Tank

It is important that the backing strip be held tightly against the under side of the seam. This is generally done with clamps spaced at intervals varying with the thickness of the material. Copper or aluminum alloy clamps should be used on the top or weld side of the seam. If the work is to be tack welded, however, no clamps are necessary other than those needed to hold the work and to control distortion. A dam should be provided in all cases to prevent the powdered flux from being blown away by the arc.

For welding 2S and 3S aluminum alloys, 2S filler metal is recommended. Welding rod of the 2S type gives best ductility in 2S and 3S material. For the other weldable alloys 43S welding rod, hard or half hard, gives better strength and reduced tendency to cracking. The rod size is increased as the thickness of the metal increases and should be selected so as to permit feeding it at a slightly higher rate than the rate of travel speed. The welding rod must be in contact with the work and fed directly into the arc. The rate of feed controls the amount of reinforcement.

The flux used in all cases is deposited on the seam in powdered form, about 2 in. ahead of the electrode. Care should be taken to use the proper amount of flux as this determines to a large extent the outward appearance of the weld, the density and ductility of the weld, the stability of the arc and the elimination of porosity. Too little flux will produce a rough uneven appearance and the fused flux will be hard to remove from the weld. Too much flux produces a good appearance but will result in possible porosity at the fusion line and reduced ductility.

The fused flux will, under normal operating conditions, be readily removable and leave a clean smooth weld. Adhering slag may be removed by scrubbing

with a wire brush and hot water, followed by washing in hot 10% sulfuric acid or hot 5% nitric acid, and rinsing with hot water or steam.

Current, Voltage and Speed.—The proper current for welding is the minimum which will produce continuous complete penetration. Excessive current will cause burning through. The proper voltage is the minimum which does not interfere with the proper melting of the welding rod. The travel speed, however, is the basic adjustment. All other adjustments of current, speed of filler metal feed and rate of flux deposit depend on the travel speed. The rates of travel speed given in Table 12 are conservative.

The mechanical properties of welds made in aluminum and its alloys are good. Welds are of sufficient strength in types 2S and 3S to cause tension test samples to fracture in the heat-affected zone near the weld. Tensile strength of other types will be in excess of 20,000 psi., but less than the strength of the annealed parent metal. This is due to the composition of the weld and application of heat from the welding operation.

The ductility of the outer fibers, as measured by a free-bend test, will vary from 10 to 50% on 2S and 3S. Ductility on other types is relatively lower, depending on the alloy type. Welds are free of porosity.

Although most seams in aluminum fabrication are made with butt joints, other types of joints (lap, edge, corner) can also be welded, and where there is sufficient volume, the use of automatic equipment may be advantageous. Figure 17 shows a typical aluminum fabrication by automatic carbon-arc welding.

Surfacing With Alloyed Powder And Carbon-Arc

A fine-grained alloyed powder can be applied with the carbon-arc to obtain a hard thin surfacing. Abrasion-resistant deposits as thin as 0.025 in. can be made and, when properly applied, a hardness of approximately Rockwell 54C can be obtained. This hardness will vary somewhat depending on the amount of admixture of alloy and base metal. The alloy develops its full hardness in the as-deposited condition, maintains its hardness and resists scaling at high temperatures. The deposit can be softened by annealing.

Table 12 — Complete Penetration Butt Joints In Aluminum By Automatic Carbon-Arc Welding

Plate Thickness, In.	Voltage	Current, Amp.	Filler Metal: Feed, In./Min.	Filler Metal: Feet of Weld per Lb. of Rod	Filler Metal: Diameter, In.[a]	Flux: Feed, Oz./Min.	Flux: Feet of Weld per Lb. of Flux	Travel Speed, In./Min.	Backing Strip Groove, In. Depth x Width	Clamp Spacing, In.
0.064	25	140	36	65	1/8	0.5	100	36	0.025 x 1/4	1/2
0.125	28	300	36	50	1/8	0.9	40	28	0.050 x 3/4	3/4
0.187	29	325	25	35	5/32	1.1	24	20	0.050 x 3/4	1
0.250	30	350	20	35	5/32	1.1	19	16	1/16 x 3/8	1 1/4
0.312	30	375	20	30	5/32	1.1	17	14	1/16 x 3/8	1 1/4
0.375	32	400	20	25	5/32	1.1	14	12	1/16 x 7/16	1 1/8
0.500	33	425	12	20	3/16	1.1	10	8	1/16 x 7/16	1 1/8
0.625	35	450	12	15	3/16	1.1	7	6	1/16 x 7/16	1 1/8

[a] 1/8-in. wire = 0.015 lb./ft. or 67 ft./lb. of wire.
5/32-in. wire = 0.023 lb./ft. or 43 ft./lb. of wire.
3/16-in. wire = 0.033 lb./ft. or 30 ft./lb. of wire.

Its corrosion resistance compares favorably with stainless steel but it should not be used where impact is excessive.

Powder should be spread evenly over the area to be surfaced and to a depth of two to three times the desired thickness of deposit. Using a sharp, well-tapered carbon with straight polarity, the powder is fused with a weaving motion. The exact heat required depends on size of work. Enough heat should be used to obtain a free-flowing puddle, but not enough to penetrate too deeply into the base metal. Whenever possible, weaving for the full width of deposit should be used to fuse the desired depth in one pass. If more than one pass is required, the work must be kept hot.

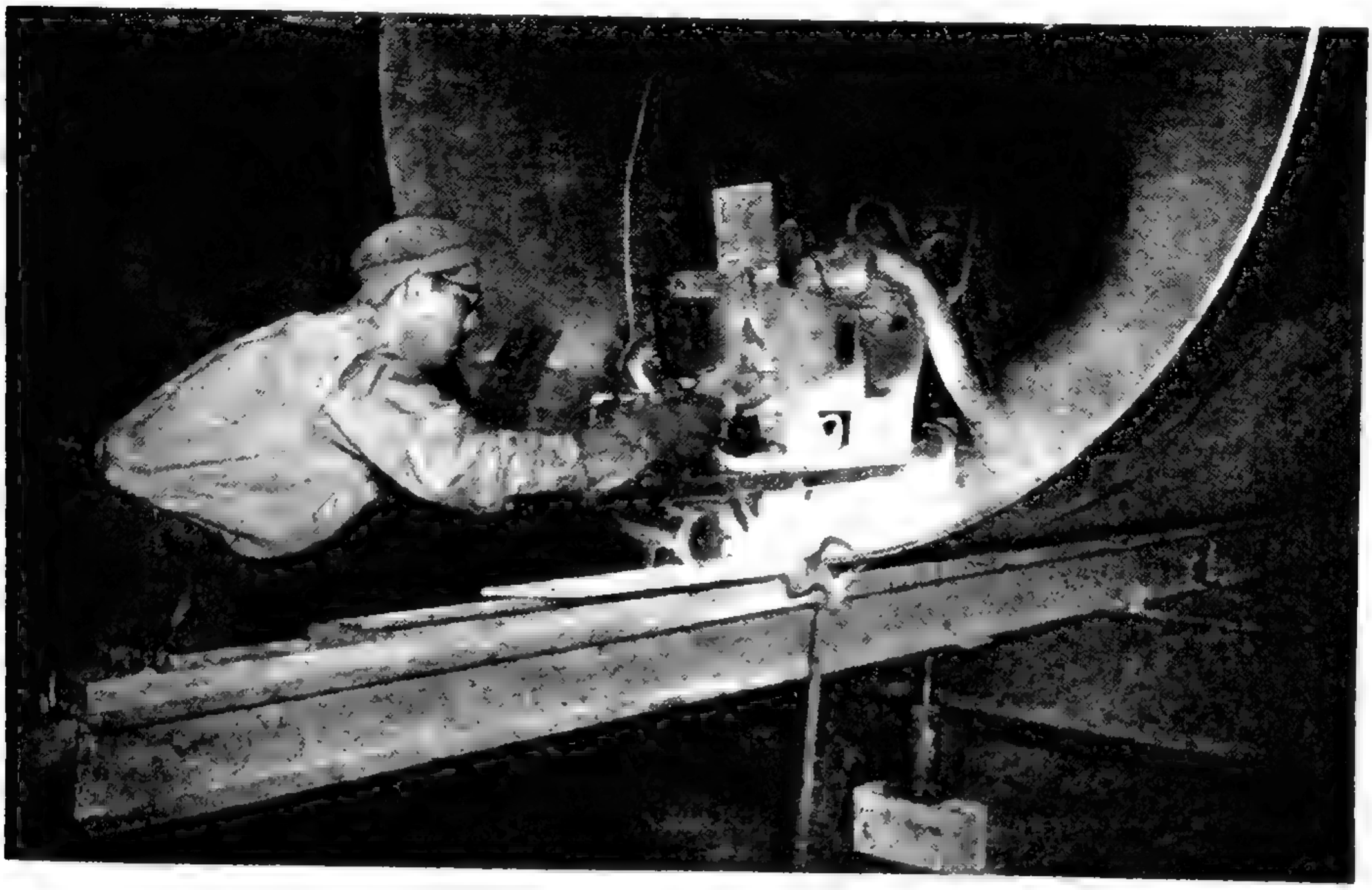

Fig. 17.—Welding All-Aluminum Tank Car

BIBLIOGRAPHY

1. *Carbon Arc Welding of Naval Brass*, K. L. Walker, The Welding Journal, January 1944.
2. *Carbon Arc Welding*, G. E. Stedman, Welding Engineer, January 1945.
3. *Automatic Carbon Arc Welding*, W. J. Conley, Welding Engineer, February 1945.
4. *Railroad Tank Cars of All-Welded Aluminum*, R. E. Haas, The Welding Journal, October 1945.
5. *Procedure Handbook of Arc Welding Design and Practice*, The Lincoln Electric Co., Eighth Edition, 1945.
6. *Arc Welding of Copper and Copper Base Alloys*, The Welding Journal, October 1947.
7. *Inert-Gas Carbon-Arc Welding of Red Brass*, L. P. Benva, The Iron Age, June 1948.

CHAPTER 10

SHIELDED METAL-ARC WELDING, BARE METAL-ARC WELDING, IMPREGNATED TAPE METAL-ARC WELDING*

FUNDAMENTALS OF PROCESSES

Definitions and General Description

Shielded Metal-Arc Welding.—An arc-welding process wherein coalescence is produced by heating with an electric arc between a covered metal electrode and the work. Shielding is obtained from decomposition of the electrode covering. Pressure is not used and filler metal is obtained from the electrode.

Bare Metal-Arc Welding.—An arc-welding process wherein coalescence is produced by heating with an electric arc between a bare or lightly coated metal electrode and the work and no shielding is used. Pressure is not used and filler metal is obtained from the electrode.

Impregnated-Tape Metal-Arc Welding.—An arc-welding process wherein coalescence is produced by heating with an electric arc between a metal electrode and the work. Shielding is obtained from decomposition of an impregnated tape wrapped around the electrode as it is fed to the arc. Pressure is not used and filler metal is obtained from the electrode.

The basic principles of all three of these processes are the same. They differ by the manner in which the electrode and shielding, if any, is provided. In the application of metal-arc welding, the control of the three variables—speed of travel, amperage and arc voltage is the primary problem. In manual welding, the welder controls two of them—arc voltage and speed of travel. In semi-automatic arc welding the operator controls only speed of travel, and in fully automatic arc welding all variables are preset, maintained and controlled by a suitable mechanism.

The chemical, mechanical, and electrical variables involved and over which the welder has no control in the actual welding operation are to a greater or lesser degree taken into account in the design and manufacture of equipment and materials used.

Principles of Operation

A general description of the equipment used in metal-arc welding will be found in Chapter 8. Fundamental considerations in the design and manufacture of such equipment will become apparent in the discussion and explanation of the various phenomena involved. The arc develops intense heat which melts the metal to be welded and forms a molten pool, while at the same time the electrode tip melts and is carried across the arc into the molten pool (see Fig. 1). The usual current range for manual operation is from 15 to 400 amperes. The voltage across the arc ranges from 14 to 24 volts with bare or lightly coated electrodes and from 20 to 40 volts with the covered electrodes.

Mechanism of Weld Metal Deposition

In metal-arc welding a number of forces are involved, in varying degrees, in the transfer and retention of molten filler metal. Among the forces involved are the following:

1. Vaporization and Condensation.—The energy available in the arc is suf-

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*Prepared by a committee consisting of J. B. Arthur, Consolidated Western Steel Corp., *Chairman;* J. J. Chyle, A. O. Smith Corp.; A. N. Kugler, Air Reduction Sales Co.; J. R. Morrill, The Lincoln Electric Co.; E. E. Tisza, Air Reduction Sales Co.; R. F. Wyer, General Electric Co.

ficient to vaporize only a small percentage of the total amount of metal passing across the arc. However, of that portion of the metal at the end of the electrode which is vaporized by the intense heat of the arc, some is condensed in the pool on the work which is at a much lower temperature than the electrode tip. Some of it escapes to the surrounding air and appears as spatter. Most of the metal is transferred from the electrode to the work with all types of electrodes, in all positions, and with both a.c. and d.c. power.

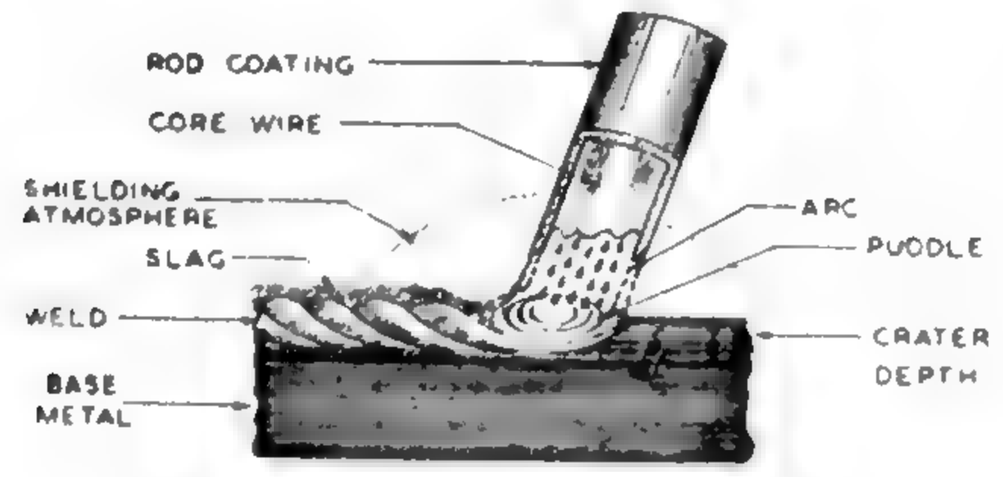

Fig. 1.—Schematic Representation of Shielded Metal Arc

2. *Gravity.*—In transferring metal across the arc it does not appear that gravity is an important factor. The rate of metal transfer across the arc, as measured by melting rate of the electrode, is practically the same when welding in the overhead as when welding in the flat or horizontal position.

3. *Pinch Effect.*—The high current passing through the molten globule at the time of the short circuit results in a radial compressive force which tends to pinch the molten globule and detach it from the electrode. The magnitude of this force and the amount of metal transfered in this manner are questionable.

4. *Surface Tension.*—This is no doubt a very important factor in retaining the molten metal in the pool on the work However, in transferring the metal across the arc gap when no short circuit exists, it is difficult to correlate any surface tension effects. When a globule short-circuits the arc, surface tension draws the metal into the molten pool, but such a force has no tendency to project any particles of metal through space.

5. *Gas Stream from Electrode Coverings.*—The velocity and movement of the ionized gas stream undoubtedly tends to give the small particles in the arc gap a movement and velocity in the same direction. It is to be noted, however, that electrodes with little gas-producing constituents in their coatings have arc characteristics such that the metal passes across the arc gap in the form of numerous small globules which are traveling at a considerable velocity.

6. *Carbon Monoxide Evolution from Electrode Wire.*—This explanation for metal transfer is predicated on the basis that carbon monoxide is evolved within the metal melting at the electrode tip, causing miniature explosions which project molten metal away from the electrode. This theory is supported by the fact that neither bare wire electrodes of very high purity iron nor of killed steel (which has been almost completely deoxidized in casting) can be used successfully in the overhead position. In other words, the causes of transfer, spatter and crater formation are attributed to the decarburizing reaction in molten steel.

7. *Pressure on the Cathode Spot.*—The cathode spot pressure on the molten globule of metal at the electrode tip depresses the liquid at this point. This depression causes the arc to shift to the high point and in turn depresses this in the same manner. In this way waves are produced in the molten metal which finally splash high enough to short-circuit the arc, after which surface tension acts to attract metal into the pool. This theory does not explain the action of d.c. reverse polarity, in which case the cathode spot is on the work, nor does it explain the condition where substantial amounts of gas are not available in the electrode, in which case overhead welding could not be done.

Results of work done on the arc phenomena associated with electrodes moving at high speed indicate that under conditions of a moving anode system, the formation of discrete anode spots has been observed. Each spot formation is accompanied by a jet of ionized vapor ejected at right angles to the surface and accompanied by metal particles and globules traveling at high velocities. Once such an anode jet is started, it remains fixed at the starting location and produces an anode spot. The arc does not maintain a steady action, but acts in a series of spurts producing an anode spot every time such action occurs. These anode spots are small in area, indicating

current densities in excess of 50,000 amp. per square inch.

The frequency of anode spot formation is greater than the frequency of globule transfer. Anode spot phenomena are closely associated with the cathode spot phenomena and undoubtedly clarify some of the missing explanations in this theory. The presence of this jet action has not been correlated to fundamental welding arc properties as yet.

8. Gas Pressure in Metal at Electrode Tip.—The expansion of gases in the metal at the electrode tip is believed to be a primary force in the transfer of metal across the arc. When these gases and vapors are liberated rapidly, they may occasionally cause small particles to leave the tip of the electrode at a high velocity. Another explanation is that they are formed below the surface of the molten metal and because of the surface tension of the liquid the expansion of the gases forms bubbles of metal on the tip of the wire. The size of the bubbles depends on the extent of gas evolution. They may burst due to pressure alone or they may expand until the arc is short-circuited. On bursting, they produce a spray of fine particles and on an arc short-circuit, they are literally exploded into fine particles by the high current passing through the thin film. The phenomena described may be attributed to impurities contained in the wire. From visual observation or high-speed motion pictures, it is not possible to distinguish bubbles from solid drops, but the rapidity of formation and disappearance is strong evidence for bubbles.

A comparison of the electrical performance of bare metal electrodes with shielded metal electrodes shows that short circuits with bare electrodes are more frequent than with covered wire, and there is a longer short-circuit duration with bare electrodes than with covered electrodes. This may suggest bubble formation and also that many bubbles burst without touching the work.

Arc Crater

The base metal terminal is similar to the electrode terminal in that liquefaction and volatilization are localized and there is a sharp temperature gradient. This heat localization produces a depressed area or crater. Dimensions of the crater are dependent on temperature, oxidation, surface tension, arc voltage and other factors affecting fusion. Crater depth during welding is a definite indication of penetration. However, the depth of crater in the completed weld is not necessarily indicative of this feature since the crater may have been filled or partially filled when the arc was broken.

Weld craters are caused by :

(*a*) Expanding gas pressure or electron stream pressure from the electrode tip (arc blast), both of which blow the liquid metal toward the crater edges, and

(*b*) Temperature gradient from maximum at the center. Surface tension varies with temperature, increasing as the temperature decreases. These differences in surface tension upset the equilibrium of the molten metal, causing concentric waves of metal to move out from the center and solidify on the colder edges or at the rim of the crater.

Metallurgical Zones

Weld metal is that portion of the base and deposited metal which has been melted during the welding period. The heat-affected zone is that portion of the base metal which has been metallurgically changed by the heat of welding. It consists of three distinct zones—the overheated section next to the weld metal, the annealed section and the transition section adjacent to the unaffected base metal.

The mechanical properties and chemical composition of each zone, that is, weld metal, heat-affected zone and base metal, are dependent on the properties of the base metal and the welding variables present. The ideal weld is one in which the properties of the weld and weld zones are identical with those of the base metal. To this end effort is usually made to have the chemical properties of all zones approximately the same. The mechanical properties are somewhat different due to metallurgical changes and, of course, change with various postheat treatments of the structure. Table 1 shows these variations as reflected by average hardness measurements of a weld specimen with and without postheat treatments.

Arc Stability

Qualitatively, arc stability refers to the tendency of the arc to burn steadily in spite of the continually changing conditions during the course of welding.

This implies a uniform flow of heat to the work along with a steady rate of metal deposition in the face of transient forces tending to alter circuit conditions, to extinguish the arc or to deflect it into space.

Quantitative study of arc stability is limited in positive results as yet; however, a distinct relationship between root mean square deviations in arc current and voltage and the average values of arc current and voltage, as well as a distinct relationship between short-circuit occurrences and average values of arc current and voltage, are indicated.

1. Electrical Effects.—The electrical load during arc welding is continually varying because the electric circuit is periodically shorted. In order to stabilize the arc, it is necessary that the welding machine voltage should rise very quickly when the current decreases, and conversely, drop quickly when the current increases. It is not sufficient that the voltage change should be large, but it must also respond quickly since the electrical circuit is periodically shorted during metal-arc welding. This condition occurs in several ways, such as by touching the electrode to the work in order to strike the arc, by accidentally shorting out the arc, and by globules of metal being transferred, actually bridging the gap between electrode and work. In every instance where there is a short circuit, the voltage drops almost to zero. As the short circuit is cleared, the full arc voltage is required practically instantaneously to keep the arc going and to avoid *pop-outs.*

Table 1—Hardness of Different Regions in Weld Zone SAE 1040 Steel, Medium-Carbon Electrodes O. 20% C (Rockwell)

Pre-heated	An-nealed	Base Metal	Heat-Affected Zone	Weld Metal
No	No	93 R_B	24 R_C	34 R_C
No	1350°F	93 R_B	95 R_B	97 R_B
600°F.	No	93 R_B	97 R_B	84 R_B
600°F.	1450°F	93 R_B	93 R_B	82 R_B

Because of the above facts, it is essential that a *drooping* volt-ampere characteristic be used in order to limit the short-circuit current. The static volt-ampere characteristics have very little to do with the performance of the welding machine, but they show the range of possible current adjustment and show the change in open-circuit voltage for any current setting. Modern single operator d.c. welding machines have two general types of volt-ampere characteristics. Compound-wound d.c. generators have a series and/or shunt field control. Changing the shunt field control raises or lowers the open-circuit voltage and results in a group of essentially parallel volt-ampere curves. Change in the series field control does not affect the open-circuit voltage, but results in a group of volt-ampere curves having various slopes, all of which have the same open-circuit voltage.

The cross-field generator type of d.c. welding machine produces a group of volt-ampere curves, with different slopes without a great change in the open-circuit voltage.

Transformer and constant potential welding machines develop a series of varying slope volt-ampere curves, all of which originate from an approximately constant open-circuit voltage.

With manual welding it is impossible for the welder to hold a constant arc length. Varying arc lengths cause arc voltage to vary and in turn produce corresponding changes in welding current. The greater the slope of the volt-ampere curve within the welding range, the lower the current change is for a given voltage change. A steep characteristic produces small current changes for a given arc voltage change. Welding machines with this characteristic are known as *constant current machines.* A flat characteristic produces a large current change for a given change in arc voltage. If the slope is such that the product of current and voltage is constant for a given setting, the machine is known as a *constant energy machine.* Tests made on electrodes indicate that under normal welding conditions the melting rate is directly proportional to the current and almost independent of arc voltage. (See Fig. 2 which shows this graphically.) Taking this into account, it can be said that in many welding operations it is desirable to maintain a constant current in order to obtain maximum welding speed and quality; therefore, in such cases a steep volt-ampere characteristic is desirable. In other cases, a flat volt-ampere characteristic might be desirable so that the

welder can control welding current within small limits by varying arc voltage conditions surrounding the welding operations. However, fundamental research on the nature of the arc and tests on various types of arc-welding machines show that the adjustment of the open-circuit voltage has no effect on the deposition rate or on the penetration.

In all cases it is important, in order to maintain an arc, that the available impressed voltage (open-circuit voltage) be higher than any voltages which might occur in welding operations. There is some question regarding the effect of open-circuit voltage on the ease of striking an arc. Ordinarily, the open-circuit voltage is not high enough to automatically establish the arc; therefore, the arc must be struck by first touching the electrode to the work (short circuit) and then withdrawing it. If this time is appreciably long, the arc is actually established from short-circuit conditions rather than from open-circuit conditions.

The difference in open-circuit voltages normally used will probably have no effect in the case where the base material is covered with an insulating foreign material unless such material is extremely thin, in which case its resistance will be broken down. If there is a moderately high resistance, the current flowing at the instant of contact will be proportional to the open-circuit voltage. Higher currents produce greater amounts of ionization, which in turn assist in establishing the arc. Probably in a majority of all cases, the act of striking the arc breaks through the surface impurities so that small points of clean metal are exposed.

Actually, the volt-ampere characteristics of the welding machine during periods of metal transfer do not follow the static curves shown in Fig. 3. The actual volt-ampere characteristic is more nearly represented by Fig. 4. Depending on the welding machine and the circuits, the instantaneous voltage during arcing and short-circuiting may vary from lines *1* to *5* to lines *2* to *3*, respectively. Instantaneous current values may vary from points *1* to *3* or *6* to *4*. Some overshooting or undershooting may also occur on variable voltage d.c. machines.

Constant potential d.c. and a.c. welding machines have no undershoot or overshoot. Extremely high overshoot currents,—as represented by point *4*, have a tendency to increase spatter loss and low undershoot, as represented by point *6*, may cause the arc to become extinguished under certain conditions. The magnitude of this undershoot and overshoot depends on d.c. machine design. The transient volt-ampere characteristic of constant potential and a.c. machines would be represented by rectangle *1-2-3-5-1*.

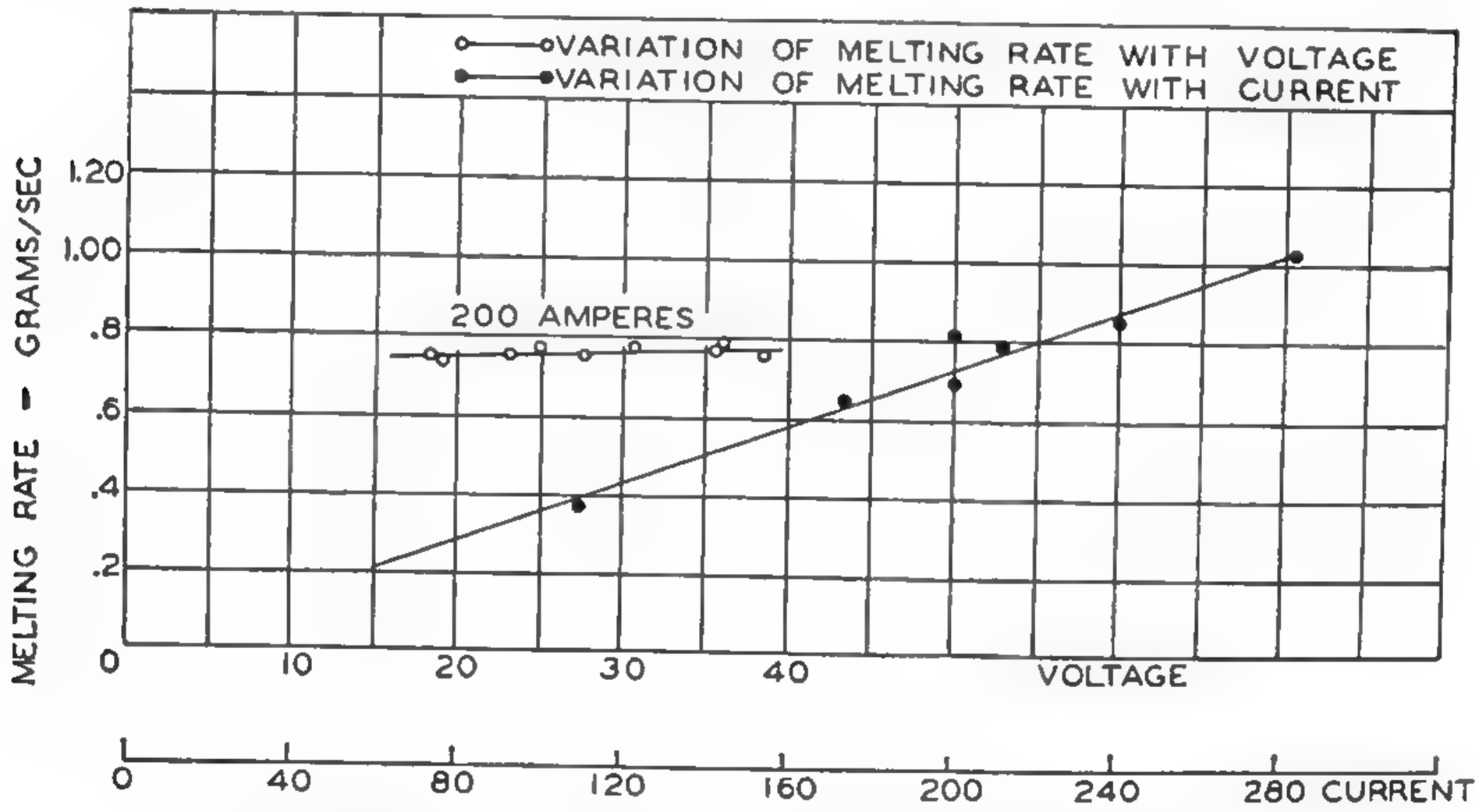

Fig. 2.—Effect of Current and Voltage on Electrode Melting Rate

2. Arc Blow.—Magnetic forces acting on the welding arc and causing the phenomenon known as arc blow are a result of the asymmetric magnetic field induced by and surrounding the path of the welding current. The distortion of this mag-

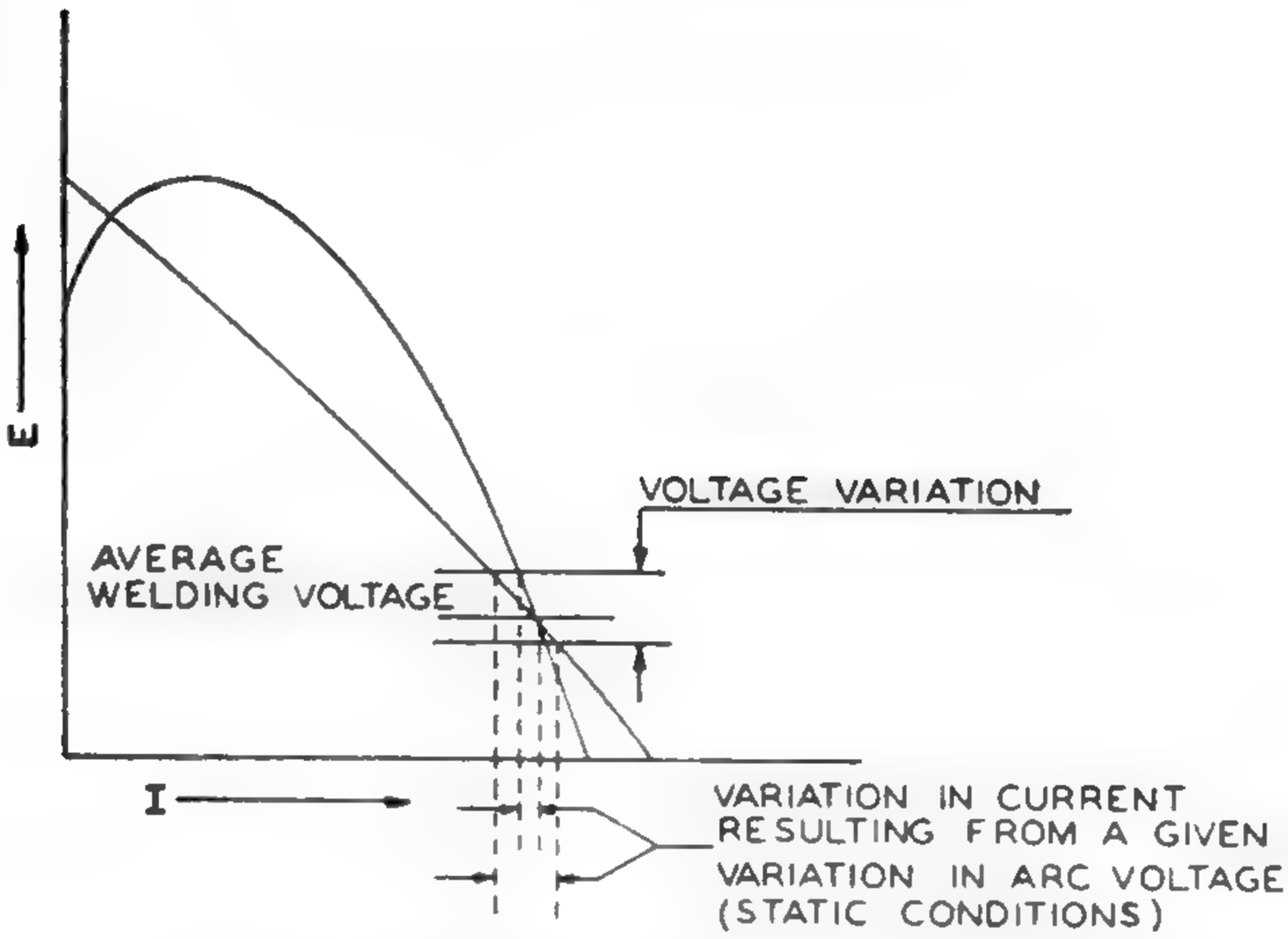

Fig. 3.—Typical Static Volt-Ampere Curves for Arc-Welding Machines

Curves show effect of variation in slope.

netic field is caused by three factors, two of which are common to both a.c. and d.c. welding.

(*a*) *Asymmetric Position of Magnetic Material about the Arc.*—The resultant force on the arc acts toward the best magnetic path or the nearer of two good magnetic paths and is independent of electrode polarity. The position of the best magnetic path with respect to the arc will change as welding progresses; consequently, the intensity and direction of the force will change. Causes for the change of the best magnetic path are: (1) A change in position of the arc and electrode with respect to the work as welding progresses along the joint; (2) the amount of weld metal deposited and the size of the air gap produced by the root or joint opening; and (3) the presence of metal in the vicinity of the arc heated above the temperature at which it becomes non-magnetic.

(*b*) *Abrupt Change in Direction of Welding Current.*—The current will take the easiest path, but not necessarily

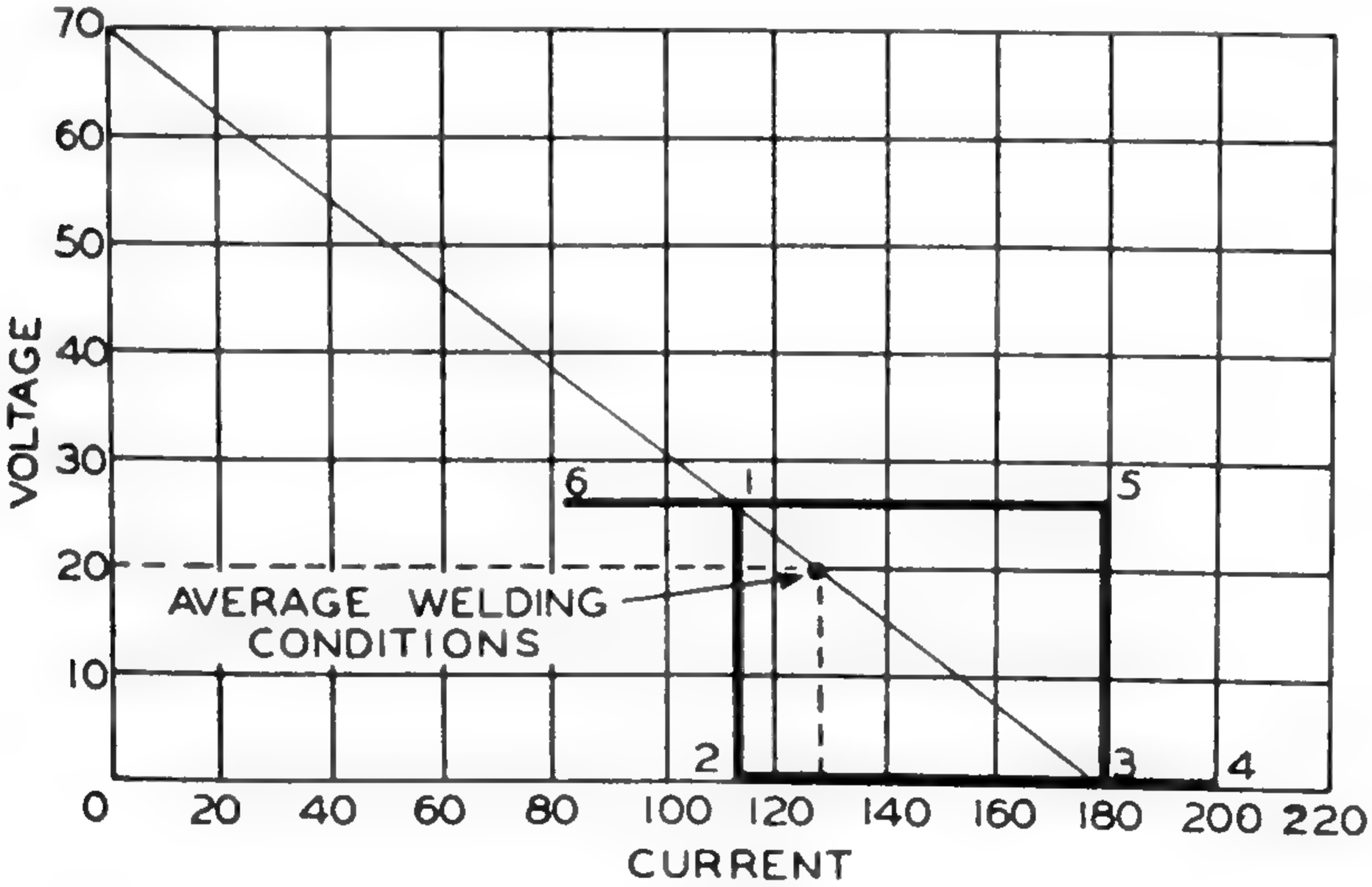

Fig. 4.—Dynamic Characteristics of Arc-Welding Machines

the most direct path through the work to the ground connection. The resultant force is opposite in direction to the current path away from the arc and is independent of polarity. In determining the location of the ground connection, care must be exercised in determining the actual path of the current through the work to the ground.

(*c*) *Eddy Currents Induced by A.C. in the Work.*—Eddy currents tend to neutralize arc forces produced by the previously mentioned cases. They generally tend toward a central distribution about the non-magnetic region of the heated metal behind the arc. The resultant force on the arc acts in the direction of welding under closed seam conditions. When welding on an open seam, between two good magnetic paths across the seam, the force is toward the nearer path. The greatest force on the arc is caused by variations in reluctance of the magnetic field around the arc. The location of the ground is of secondary importance, but may have an appreciable effect in reducing the total force on the arc. The total force on the arc may be reversed by change in ground location only when the reluctance of the magnetic path about the arc is fairly symmetrical. Magnetic forces acting on the arc may also be modified by: (1) Changing magnetic fields across the joint with steel strips, starting plates, tack welds, welding sequence, etc.; and (2) use of an external field such as produced by a permanent magnet, electromagnet, etc. An external field of the latter type is not effective when welding with a.c. unless such field is produced by an a.c. source of the same frequency as the welding current and with the proper phase relationship to the welding current. The conditions which affect the forces acting on the arc vary so widely that it is impossible to make general recommendations for reducing or controlling these forces.

3. Filler Metal Composition Effects.—In any metal-arc welding process, the chemical composition of the filler metal core wire plays an important role in arc stability and affects the mechanical properties of the weld metal. In bare metal electrodes, the composition of the wire is a major factor in determining arc stability. This is in contrast to lightly coated or covered electrodes in which arc stability is affected by the chemical and physical constitution of the coating. Arc stability is materially affected by the presence of certain elements or their oxides. Table 2 shows this in tabulated form.

Of course, the chemical composition of the filler metal also has a large effect on weld quality. Coatings used on electrodes provide an ionized path for the current and increase the fluidity of the molten metal. Metallurgically speaking, while it is of lesser importance, it is nevertheless essential that the core wire be of normalized grain structure, as the specific electrical resistance of mild steel in this condition is most suitable for arc-welding purposes. Lack of uniformity of the final heat treatment of the core wire is often responsible for the erratic behavior of electrodes.

4. Base Metal Effects.—The surface cleanliness and homogeneity of the base metal are important considerations in metal arc stability as well as determining

Table 2—Function of the Covering Constituents in Arc-Welding Electrodes

Covering Constituent	Arc Stabilizer	Slag Former	Reducing Agent	Binder	Coating Strengthener	Oxidizing Agent	Gas Shielding	Alloying Weld Metal
Gum and/or resin	..	..	B[a]	A	..	..	..	.
Cellulose	..	..	B	..	B	..	A	
Feldspar (alkali aluminum silicates)	B	A	..	..	..	..	.	.
Clay aluminum silicates	B	A	..	..	..	..	..	.
Talcs (magnesium silicates)	B	A	..	.	..	..		..
Titanates (rutile, titanium dioxide, etc.)	A	A	..	..	..	..	..	.
Iron oxides	B	A	..	..	..	A	..	..
Calcium carbonates	A	B	..	..	..	B	B	..
Asbestos	B	A	..	..	A	..	..	..
Ferromanganese	..	A	A	..	..	.	..	B
Potassium silicates or potassium salt	A	A	..	A	..	..	..	
Sodium silicates	B	A	..	A	..	..	..	..

[a] A = principal function; B = minor function.

factors in the properties of the finished weld.

Arc Voltage and Arc Length

In metal-arc welding, the arc is a gaseous conductor of electricity. It is not primarily self-starting and if extinguished must be re-established. Furthermore, several factors are essential for its continuity—ionization, molten slag (if present in the covering of the electrode), cathode spot and a method of feeding the electrode constantly in order to maintain the required distance between cathode and anode.

In the arc, there are three well-defined voltage zones known as the cathode drop, the anode drop at the terminals and the arc stream voltage. The heat dissipated in each voltage zone is proportional to the voltage. The cathode and anode drops are practically constant and are independent of arc length and current. The voltage across the stream varies with arc length but not in direct proportion thereto.

In order to reduce oxidation and porosity to a minimum, it is generally desirable to maintain a relatively short arc for the process being used. A long arc is erratic and is also inefficient as it increases spatter loss. A very short arc is impractical. The length of arc used is dependent on the type of coating in the case of covered electrodes.

Striking, Maintaining and Breaking the Arc

A metal arc is struck by touching the work with the electrode and quickly withdrawing the electrode a distance not exceeding that required for maintenance under welding conditions. When a metal arc is struck, there is a tendency for the electrode to *freeze* or stick to the work due to a sudden rush of current induced by short-circuiting of the machine. This tendency is very pronounced in manual bare metal-arc welding, and it is desirable when this process is used to employ a lateral motion to strike the arc, similar to that of striking a match.

Contact electrodes, in which the coating is an electrical conductor, are normally struck by holding them in contact with the work. The small amount of current which flows through the coating when contact is made is sufficient to start an arc. Arc length is held essentially constant by maintaining this contact with the work. Since the coating has a lower melting rate than the core wire, a deep cup is formed which prevents freezing of the electrode and shields the arc.

With some types of electrode (mainly classes AWS E6020 and AWS E6030 and aluminum-coated rods) it is necessary when striking the arc to forcibly remove the projecting covering on the electrode tip by tapping it strongly on the work.

After a metal arc has been struck, it is maintained by a uniform movement of the electrode toward the work to progressively compensate for that portion which has been melted and deposited in the weld. At the same time, the electrode is also progressively advanced in the direction of welding.

Two procedures are commonly employed to break the arc. One procedure requires that the arc be shortened and the electrode moved quickly sideways out of the crater. This method is used in manual welding when electrodes are changed and the weld is to be continued from the crater. The other procedure requires that the electrode be held stationary long enough to fill the crater and then gradually withdrawn. This method is used in manual, semiautomatic, and automatic welding when either full or partial crater elimination is desired.

When the arc is re-established in a crater, as in the first method above, it should be struck at the forward or cold end of the crater, moved backward over the crater, and then forward again to continue the weld. This procedure fills the crater and avoids porosity and trapping of slag.

Speed of Welding

Speed of welding is defined as the velocity of travel of the electrode along the seam or the velocity of travel of work under the electrode along the seam. Speed of welding is dependent on several factors including:

(*a*) Current used or burn-off rate of the electrode.
(*b*) Joint preparation.
(*c*) Analysis and properties of metal being welded.
(*d*) Fit-up.
(*e*) Process used.

Some general statements can be made regarding speed of travel. Increasing speed of travel and maintaining constant

arc voltage and current will reduce the width of bead. Increasing the speed of travel and maintaining conditions as above will increase penetration until an optimum speed is reached at which penetration will be maximum; increasing the speed beyond this optimum will result in decreased penetration. Actually, the limiting speed is usually the highest speed at which the surface appearance remains satisfactory. The speed of welding and the rate of heat input affect the structure and hardness of the weld. All other things being equal (mass of base metal, temperature, amount of weld metal deposited in unit time, etc.), a bead deposited at high speed produces a greater hardening than one deposited at low speed with a consequently higher heat input per unit length of joint.

It is to be noted that *time for welding* is the sum of arc time, plus handling time, plus losses due to inefficiency. In other words, it is the arc speed (speed of travel for complete joint) divided by the welding efficiency (operating factor) and is in no sense absolute. (See Chapter 41 for information on estimating costs.)

Angularity of Electrode to Work

The angular position of the electrode to the work may determine to a marked degree the quality of the weld metal, freedom from undercutting and slag inclusions, the ease with which the filler metal is deposited and the uniformity of fusion and weld contour as affected by the influence of surface tension and gravity on the molten metal. Recommendations of manufacturers should be followed in all cases.

The *lead angle* of the electrode is the angle between the joint and the electrode taken in a longitudinal plane, whereas the *work angle* is the angle between the electrode and the work taken in a plane normal to the joint plane (see Fig. 5). Increasing the lead angle in the direction of welding ordinarily builds up a bead. Too large a work angle may result in undercutting.

Joint Preparation

Joint geometry is determined by code and specification requirements for the finished product; design considerations as above and in line with quality and economics; and post-treatment of the weldment.

The method of joint preparation can be one of the following: machining, chipping, shearing, oxygen (oxy-acetylene or oxy-fuel gas combination) cutting, grinding or flame gouging. The method to be used depends on joint shape, facilities available, quality desired, etc. (Chapters 39 and 40 cover design and properties of welded joints).

General Design Practices

The ease with which component parts can be joined together by welding to form a complete structure often causes the designer to lose sight of the economies of welding. A good design is one that contains the least number of parts and the minimum amount of welding that is adequate for fabrication and service requirements. A careful analysis should be made of each structure to insure that it can be fabricated economically. Materials having satisfactory weldability should be used. Welds must be designed, located and made to keep distortion within acceptable limits. Rigid joints should be avoided as much as possible consistent with tolerances for

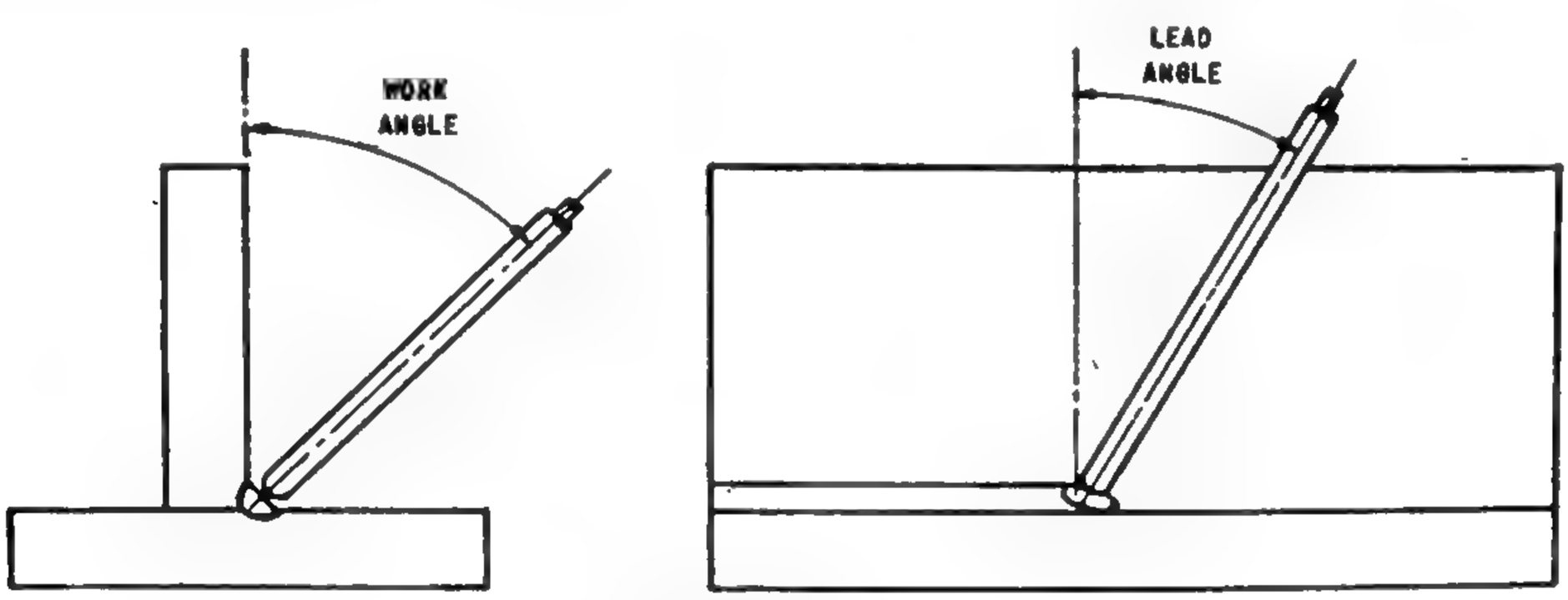

Fig. 5.—Electrode Work Angle and Lead Angle

distortion to help prevent cracking during fabrication or in service.

The following factors should be considered in the design:

(*a*) A minimum amount of welding, consistent with the stresses in all component parts, should be used except in those cases where leakproof welds, minimum fillet size requirements, appearance or machining stresses determine the amount of welding required.

(*b*) Welds should be easily accessible for manufacturing, repair and testing with minimum handling. Correct electrode angles, physical dimensions conforming to the use of standard length electrodes and electrode holders for manual welding, or room for electrode leads and contact nozzles for automatic welding must be considered in providing accessibility.

(*c*) The position in which welds will be made should have the following order of preference: flat, horizontal, vertical and overhead for fillet welds and flat, vertical, horizontal and overhead for groove welds.

(*d*) Joints should be designed so as to minimize, in so far as reasonably possible, stresses due to shrinkage, secondary bending and eccentricity.

(*e*) Machining allowances must take into consideration the following factors: Assembling; shrinkage due to welding; distortion of base metal; and variations (mill tolerances, etc.) of rolled sections

(*f*) Size of fillet welds should be held to $^5/_{16}$ in. or less whenever possible in order to facilitate making welds in a single pass, thus reducing welding costs.

(*g*) It is considered good practice to limit the minimum size fillet weld that can be used on a given thickness of plate.

Materials Used in Metal-Arc Welding

Electrodes.—In metal-arc welding the electrodes used for supplying filler metal can be:

Bare wire:
- Coating applied before drawing (sul-coated or sul-finished).
- Coating applied after drawing
- No coating of any kind.

Heavy covered mild steel electrodes:
- Cellulosic covering type.
- Rutile covering type
- Mineral covering type.
- Lime covering type
- Low-hydrogen covering type
- Knurled heavily covered type

Bare wire with impregnated tape attached.

Complete classification and specifications for electrodes are covered in chapters 38 and 61.

General Effect of Use of Metal-Arc Welding on Base Metal

Tables 3 and 4 contain more concise tabulations of the effects discussed herein.

Warping—Distortion

Distortion due to metal-arc welding can be controlled and reduced to a minimum by:

Use of automatic metal-arc welding with the attendant higher speed, greater deposition rate and minimum number of starts and stops.

Preheating.

Pre-springing or initial reverse distortion produced by mechanically setting or bending a part in an opposite direction to which warpage is expected so that the effect of welding is to restore the part to its desired shape.

Strong-backs, hold-downs or jig methods.

Drum-heading by which boundaries of the weldment are held in a permanent or temporary restraint.

Tack welding.

Design.

Welding sequence using either wandering, balanced chain or other sequence of welding as applied to assembly sequence of complete weldment.

If distortion has occurred, corrective measures which may be applied are:

Alternate heating and cooling of affected locations.

Hammering, press work or other mechanical correction.

Shrink welding in which heat is supplied by running weld beads on the convex side of the buckled area

Mechanical correction and additional welding of auxiliary members to retain such correction.

Shrinkage

Shrinkage of the weld and base metal can be controlled and reduced to a minimum in non-preheated weldments by:

Reduced root opening.

Use of a minimum amount of welding.

Use of welds of smallest size which will still give a product fulfilling all requirements.

Use of the minimum number of layers required to satisfy weld properties

Maximum use of intermittent welding

Peening of all except root and face passes.

Proper selection of welding sequence.

Due to the variables involved, it is impossible to predict or establish shrinkage values for metal-arc welds which can be applied to all types of products and materials. This is a matter of general experience.

Residual Stress Formation

Residual stresses cannot be entirely avoided and as these stresses may exceed the yield strengths of base and weld metal, it is sometimes desirable to use preheating or stress-relieving methods as covered in Chapter 43. These methods are definitely required if the finished weldment requires machining to close tolerances.

Metallurgical Effects

Adverse metallurgical effects can be controlled, minimized or corrected by preheat, thermal post-treatment and use of correct electrodes as, for example, high-chromium stabilized electrodes for medium-chromium stainless applications.

Weld Quality

The common defects encountered in metal-arc welding and their detection by various inspection methods are discussed in Chapter 42, Inspection of Welding.

EQUIPMENT USED

The machines and other equipment used for the arc-welding processes are discussed in detail in Chapter 8. This section contains a brief summary of the equipment generally used.

Manual Welding Equipment

In addition to a source of welding power (a.c. transformer, d.c. generator, a.c. generator or a.c. rectifier) the following additional equipment is used:

Welding machine accessories such as oscillators, voltage-protective devices, crater eliminators, remote control devices, generator- or motor-idling devices, resistor banks, etc.

Work-Handling Equipment.

Auxiliary equipment such as cables, cable connectors, electrode holders, ground connectors, helmets, hand shields, protective clothing, chipping and slag-removal hammers, weld gages, brushes, etc.

Machine Welding Equipment

In addition to a welding head it is necesarry for machine arc welding to provide suitable work handling equipment, which may be classified as follows: (1) equipment in which the work is held stationary and the electrode moves over it, and (2) equipment in which the work moves under a stationary head.

In designing, building or purchasing work-handling equipment for automatic metal-arc welding, the following points must be taken into consideration:

(*a*) The fabricated product to be automatically welded must first have been welded successfully manually.
(*b*) Parts to be welded must be positioned so that welds are made in flat or horizontal positions. (Some welding in the vertical position has been accomplished, but this is extremely unusual.)
(*c*) Fit-up between parts to be welded must be uniform and close.
(*d*) It is desirable that all seams be straight whether flat or circular.
(*e*) Some method of backing up the joint must be provided, if required.
(*f*) Straight seams (or electrode aligning mechanisms if used) must be held exactly parallel to the direction of motion.
(*g*) Circular seams must be revolved in a true circle without wobble.
(*h*) Speed of travel of moving parts must be steady and adjustable over a suitable welding speed range.
(*i*) Production capacity required.
(*j*) Maintenance costs of the equipment.
(*k*) Initial purchase or cost price.

Standard work-handling equipment for automatic metal-arc welding consists of the following items. These can be adapted at times for quite a diversified line of work. In other cases specially designed equipment is required.

(*a*) Work-holding positioners.
(*b*) Head-travel carriages.
(*c*) Head-mounting pedestals.
(*d*) Turning rolls.
(*e*) Portable power units such as pipe rotators, etc.
(*f*) Work skids equipped with hold-downs, air jacks, etc.

Table 3—Influence of Base Metal Variables in the Production of a Serviceable Structure (Shielded Metal-Arc Welding)

Mechanical Properties of Base Metal Determined by	Principal Base Metal Variables	Effect on Base Metal Immediately Adjacent to Weld (Heat-Affected Zone)			Effect on Weld Metal and Fusion Zone (Interfused Base and Filler Metals)			Effect on Completed Weldment (Magnitude of Locked-Up Stresses)
		Susceptibility to Cracking During Welding						
		Underbead Cracks[a]	Other Thermal Cracks	Properties of Metal in Absence of Cracks	Susceptibility to Welding Cracks	Soundness (Exclusive of Cracks)	Properties of Sound Weld Metal	
	Carbon content	Increase with carbon content	Increase with carbon content	Strength increases, impact resistance decreases with increase in carbon content	General increase with carbon content	Generally, no effect[b]	Strength increases, impact resistance decreases, with carbon pickup	Increase with carbon content
	Hardenability	Increase with hardenability[c]	Increase with hardenability	Strength increases with hardenability. Impact resistance increases with hardenability until martensitic type microstructure forms, then decreases with hardness of final structure[d]	General increase with hardenability	Certain alloys may contribute to weld metal porosity[b]	Strength increases with alloy pickup from base metal[e]	Increase with hardenability
	Prior heat treatment	Decrease by a heat treatment, which eliminates hydrogen present from prior processing, or which stabilizes carbides	Increase with yield strength and decrease with increasing ductility as established by prior heat treatment	Heat treatment which stabilizes carbides lowers effective hardenability during welding cycle	Increases with yield strength; decreases with increasing ductility, as established by prior treatment	No effect	No effect	Increase with yield strength, decrease with increasing ductility as established by prior treatment
	Nonmetallic content and distribution	Certain nonmetallics (as sulfur) may react with and eliminate hydrogen dissolved in molten weld metal	Cracks may start at nonmetallics, especially if elongated by rolling or segregated at grain boundaries	Inclusions may decrease ductility and impact resistance, especially if elongated at grain boundaries, effect is very marked when heat-affected zone has high hardness	Some nonmetallics may contribute to weld metal cracking	Certain nonmetallics (as sulfur) may contribute to weld metal porosity or slag inclusions[b]	General decrease in strength and impact resistance with increased nonmetallic content[e]	No effect
	Porosity and surface defects	Decrease with increased porosity which permits escape of hydrogen diffused into base metal	Cracks may originate at porosity or surface irregularities	Strength and impact resistance decrease with increase in porosity or surface irregularities, depending largely upon location	No effect known	Surface oxides may contribute to weld metal porosity and slag inclusions	No effect known	Surface irregularities give rise to stress concentrations

[a] Underbead cracks are not formed if electrode coating is low in hydrogen compounds.

[b] Depends, to a large extent, upon specific gas and fluxing reactions during welding.

[c] Effect of certain alloys on solubility and diffusibility of hydrogen may have undetermined influence. Carbide stabilizing alloys may decrease effective hardenability during welding cycle.

[d] In absence of cracks, best combination of strength and impact resistance is obtained when martensitic-type microstructure is formed in heat-affected zone by first passes and is tempered to a hardness approaching that of the base metal by subsequent weld passes or postheat treatment.

[e] Impact resistance increases with alloy pickup from base metal for usual low-carbon ferritic weld metals.

Table 4—Influence of Welding Procedure Variables in the Production of a Serviceable Structure (Shielded Metal-Arc Welding)

Principal Welding Procedure Variables	Effect on Base Metal Immediately Adjacent to Weld (Heat-Affected Zone)			Effect on Weld Metal and Fusion Zone (Interfused Base and Filler Metals)			Effect on Completed Weldment (Magnitude of Locked-Up Stresses)
	Susceptibility to Cracking During Welding						
	Underbead Cracks[a]	Other Thermal Cracks	Properties of Metal in Absence of Cracks	Susceptibility to Welding Cracks	Soundness (Exclusive of Cracks)	Properties of Sound Weld Metal	
Weld heat input: Increases with (1) Current and voltage; (2) Exothermic reactions in arc Decreases with increasing arc-travel speed, endothermic reactions and radiation from arc	Decrease with heat input sufficient to prevent formation of martensitic type microstructure	Increase with heat input, except when it is sufficient for low thermal gradients or low cooling rates	High heat input deepens heat-affected zone, increases amount of coarse-grained, high-temperature structure, with considerable variation of strength and impact resistance of the structure in alloy steels	Decreases with increased heat input	General improvement with higher heat input except when followed by slow cooling which may produce porosity	No definite established relationship between weld heat input and properties of sound weld metal	Locked-up stresses increase with increased heat input
Weld Cooling Rate: Increases with (1) Mass-Metal adjoining bead; (2) Thermal capacity of surroundings; (3) Conductivity of weld metal Decreases with increasing preheat temperature, interpass temperatures and insulation of slag deposit	Increase with cooling rate sufficient to form martensitic type microstructure	Increase with cooling rate	Strength increases with cooling rate; impact resistance increases with cooling rate until martensitic type microstructure forms, then decreases with increasing hardness of final structure	Increases with cooling rate	Soundness improved by slower cooling rate, except when preceded by high heat input. See above	Strength increases with cooling rate; impact resistance increases with cooling rate for usual low carbon ferritic weld metals	Locked-up stresses increase with faster cooling rate

Composition of Molten Filler Metal [b]							
Carbon content	Carbon has no known effect	Increase with carbon content [c]	Carbon has no effect	Increases with carbon content	Effect of carbon varies[d]	Strength increases; impact decreases with carbon	Increase with carbon content
Alloy Content	No effect of alloys known [e]	Increase with alloy content [c]	Alloy content has no effect	Variable, depending on alloy	Effect of alloys varies[d]	Strength and impact generally increase with alloy	Increase with alloy content
Nonmetallic content	Certain nonmetallics may eliminate dissolved hydrogen	Nonmetallic content has no known effect	Nonmetallic content has no effect	Certain nonmetallics may possibly contribute	Certain nonmetallics increase porosity	General decrease with nonmetallic content	No effect
Gas content	Increase with amount of hydrogen in solution	No effect definitely established	Hydrogen causes general embrittlement Effect decreases on aging	Hydrogen probably contributes	Effect varies[d]	Hydrogen embrittles; effect decreases on aging	No effect
Restraint on Weld Joint							
Increases with the rigidity of the structure, decreases by variation in sequence of joints welded, or deposition in joint	Growth of cracks, once formed, facilitated by increase of restraint	Increase with degree of restraint	Effect not definitely established	Increases with degree of restraint	No effect	Effect not definitely established	Locked-up stresses increase with greater degree of restraint
Reheating After Initial Deposition							
By subsequent weld deposits	Decrease when interpass temperature prevents martensitic microstructure	Decrease with sequences producing low thermal gradients or cooling rates	Strength decreases, impact resistance increases with increased interpass temperature[f]	Decreases with sequences producing low thermal gradients or cooling rates	No effect	Strength decreases[f]	Decrease with sequences producing low-thermal gradients or cooling rates
By postheat treatment (subcritical stress-relief anneal)	Does not prevent formation but limits their growth		Strength decreases, impact resistance increases with tempering time and temperature[f]	Does not prevent formation but limits their growth	No effect	Strength decreases[f]	Decrease with higher temperature, time at temperature and slower cooling

[a] Underbead cracks are not formed if electrode coating is low in hydrogen compounds.
[b] Controlled by core wire and coating compositions and atmospheric conditions.
[c] Carbon and alloy contents of weld metal are not serious factors in thermal crack formation in heat-affected zone of low-carbon, low-alloy base metals.
[d] Effects of carbon, alloy content and gas content which may tend to produce unsound weld metal are influenced by specific gas and fluxing reactions during welding; controlled to a large extent by electrode covering composition.
[e] Effect of certain alloys on solubility and diffusibility of hydrogen is undetermined.
[f] Impact resistance increases with increased interpass temperature, or with increases in annealing time and temperature, except for precipitation hardening alloys in which case the opposite effect may be obtained, deleterious effects may be obtained if austenitic type weld or base metals are reheated.

COMMON APPLICATIONS

Materials

All ferrous metals, such as cast-iron, low-carbon, medium-carbon, high-carbon, low-alloy high-tensile, stainless, corrosion-resistant and copper-bearing steels can be welded by metal-arc welding.

Aluminum, bronze, nickel, nickel alloys, and copper alloys can, in general, all be welded satisfactorily by metal-arc welding. For information on any specific material refer to the chapter on that material.

Fields or Industries

There is literally almost no field in which metal-arc welding is not used. Listed below, however, are the main fields. (For more information on any specific application refer to the chapter on that application.)

Structural Fabrication— bridges, buildings, etc.

Transportation—shipbuilding, aircraft, railroads, automotive products.

Pressure Vessels.

Pipe and Pipe Fittings.

Tanks—storage, pressure, process.

Home Appliances.

Machinery Fabrication.

BIBLIOGRAPHY

1. *Material Transference in the Welding Arc*, A. Hilpert, The Welding Journal, December 1929.
2. *Concerning Crater Formation*, G. E. Doan, The Welding Journal, July 1932.
3. *Metal Deposition in Arc Welding*, G. E. Doan and M. J. Weed, The Welding Journal, September 1932.
4. *Influence of a Magnetic Field on Art Welding*, F. R. Hensel and W. A. Maddox, The Welding Journal, October 1932.
5. *Research on Arc Welding*, G. E. Doan and J. L. Myer, The Welding Journal, November 1932.
6. *Electrical Characteristics of the Welding Arc*, S. C. Osborne, The Welding Journal Res. Suppl., November 1935.
7. *The Phenomenon of the Erratic (Unstable) Welding Arc*, G. M. Tichodeev, The Welding Journal, February 1936.
8. *An Exploration of a Modern Welding Arc*, L. J. Larson, The Welding Journal Res. Suppl., October 1936.
9. *Metal Deposition in Arc Welding*, G. E. Doan, The Welding Journal, January 1938.
10. *Crater Formation and Force of the Welding Arc in Various Atmospheres*, G. E. Doan and R. E. Lorentz, The Welding Journal Res. Suppl., February 1941.
11. *Heat Flow in Arc Welding*, E. M. Mahla, M. C. Rowland, C. A. Shook and G. E. Doan, The Welding Journal Res. Suppl., October 1941.
12. *Magnetic Arc Blow*, C. H. Jennings and A. B. White, The Welding Journal Res. Suppl., October 1941.
13. *Metal Transfer in the Metallic Arc*, L. J. Larson, The Welding Journal Res. Suppl., February 1942.
14. *The Measurement of Cooling Rates Associated with Arc Welding and Their Application to the Selection of Optimum Welding Conditions*, W. F. Hess, L. L. Merrill, E. F. Nippes, Jr., and A. P. Bunk, American Welding Society, 1943.
15. *Flex Arc Data Book*, Westinghouse Electric Corp., 1946.
16. *Coordinated Development of A.-C. Welders and Electrodes*, C. P. Croco, The Welding Journal, August 1947.
17. *Welding Arc Temperatures*, W. R Chynoweth, J. U. Jeffries, R. J. LaPante, R. J. Krieger and G. H. Fett, The Welding Journal Res. Suppl., August 1948.
18. *Arc Phenomena with Electrodes Moving at High Speed*, W. B. Kouwenhoven and T. B. Jones, The Welding Journal Res. Suppl., September 1948.
19. *An Investigation of Methods for Evaluating Welding Arc Stability and Their Application*, R. A. Wyant, L. P. Winsor and L. McD. Schetky, The Welding Journal Res. Suppl., October 1948.
20. *Heat Effects in Anode Spots of High Current Arcs*, T. B. Jones, W. B. Kouwenhoven and Merrill Skolnik, The Welding Journal Res. Suppl., October 1949.

CHAPTER 11

ATOMIC HYDROGEN WELDING*

FUNDAMENTALS OF PROCESS

Definition and General Description

ATOMIC HYDROGEN welding is an arc-welding process wherein coalescence is produced by heating with an electric arc maintained between two metal electrodes in an atmosphere of hydrogen. Shielding is obtained from the hydrogen. Pressure may or may not be used and filler metal may or may not be used.

In this process the arc is maintained entirely independent of the work or parts being welded, differing in this respect from most other arc-welding processes. The work does become a part of the electrical circuit to the extent that a portion of the arc comes in contact with the work at which time a voltage exists between the work and each electrode.

Hydrogen in its normal state, called molecular hydrogen to distinguish it from atomic hydrogen, is diatomic, that is, each molecule consists of two atoms. When an arc is established in hydrogen between two electrodes, usually tungsten, the temperature in the arc stream rises to approximately 11,000° F. (6000° C.), dissociating the molecular hydrogen into its atomic form. In the process of dissociation a large amount of heat is absorbed from the arc and is liberated on recombination at the surface of the work.

For a clear understanding of the atomic hydrogen process, three points must be kept in mind. First, the energy used for welding is supplied as kilowatts of electrical energy to the arc where it is transformed into heat at a temperature of approximately 11,000° F. Second, the establishment of an arc in hydrogen provides a temperature sufficiently high to cause molecular hydrogen to be rapidly transformed to atomic hydrogen, in which state its principal function is as a vehicle for transmitting the heat energy from the arc to the weld zone. Third, in the direction away from the arc stream, a sudden decrease in the temperature, such as occurs at the relatively cold surface of the weld area, is accompanied by a correspondingly rapid decrease in the concentration of atomic hydrogen, and a release of the heat of recombination at or near the cold surface. Thus, it can be seen that by varying the distance between the arc stream and the weld surface, the available temperature can be varied over a wide range.

The hydrogen performs several other useful functions. It is a very efficient cooling medium and, by absorbing a large amount of the heat being conducted along the electrodes from their arcing ends, which are molten, keeps the temperature of the remainder below the melting point. It also prevents air from coming in contact with the heated electrodes, which would cause them to be oxidized and rapidly consumed. In the same way, it protects the molten pool and the heated metal adjacent to it, reducing the tendency to surface oxidation after the weld is completed.

Principles of Operation

The amount of heat available for welding depends both on the welding current and the size of the fan-shaped arc. The welding current is selected before the weld is started, but the size of the fan-shaped arc and its distance from the weld surface may be varied during welding to obtain different degrees of heat. The welder must learn to keep the arc size uniform except where conditions warrant a change. When finishing a weld it is desirable to reduce the heat by drawing the arc away from the molten pool

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* Prepared by a committee consisting of J. T. Catlett, General Electric Co., *Chairman;* H. N Barnes, Cherry-Burrell Corp.; W. C. Heath, Solar Aircraft Corp.; W. Morgenthau, Clark Equipment Co.; R. F. Wyer, General Electric Co

slowly. This reduces the tendency to form a crater or to leave a porous spot, as its purpose is to prolong the molten condition of the surface, thus allowing gases, which might otherwise be trapped, to escape as solidification progresses upward. At times it may be necessary to employ the *silent* arc to effect a similar result. (A low voltage arc described on page 258.) A similar technique may be followed at any point in the welding where difficulties arise due to inaccurate spacing or improper manipulation.

Under the atomic hydrogen arc the molten pool is extremely fluid and must be fully confined to prevent movement under gravitational force. Such confinement by a special means usually is not practicable. In very unusual cases, dams of graphite, refractory material or copper may be used. Of these, graphite is to be preferred as it does not disintegrate as rapidly as bonded refractory materials, nor does it have the rapid chilling effect of copper which is likely to cause porosity due to entrapped gases.

The most satisfactory procedure is to confine the molten pool in a vessel or pocket formed by the adjacent solid metal, aided by the surface tension of the liquid metal. It is obvious that if complete penetration is to be secured, the bottom of this pocket cannot remain unmelted. If not too deep, the molten pool may be sustained by the surface tension of its bottom surface. The depth of the pool which can be thus sustained is about $^3/_{16}$ in. and, in the case of butt welds, determines the maximum thickness which can be welded with complete penetration without beveling or without sustaining the pool by some sort of backing such as previously mentioned. If the edges are beveled, care should be taken to leave a root-face not exceeding $^1/_8$ inch. Welding may be done in two or more passes or in a single pass by manipulating the arc so that the root face is welded and solidified before it is used to support the weight of the added metal. Filler metal is added to fill the groove and to build up any reinforcing bead.

Though frequently impracticable, it is always desirable to shield the underside of the weld with hydrogen for the time oxidizing temperatures prevail, or coat it with a suitable welding flux. This is particularly true in the welding of stainless steels and other alloys containing a constituent which otherwise would cause a thick crust of oxide to form, reducing effective penetration and the efficacy of the surface tension in supporting the liquid metal above. One method of using hydrogen for this purpose is to provide a welding fixture containing a groove spanning the weld zone, and wide and deep enough to avoid contact with the liquid metal (see Fig. 1). Hydrogen fed into this groove at a very low pressure will prevent oxidation and in many cases will reduce oxides already present.

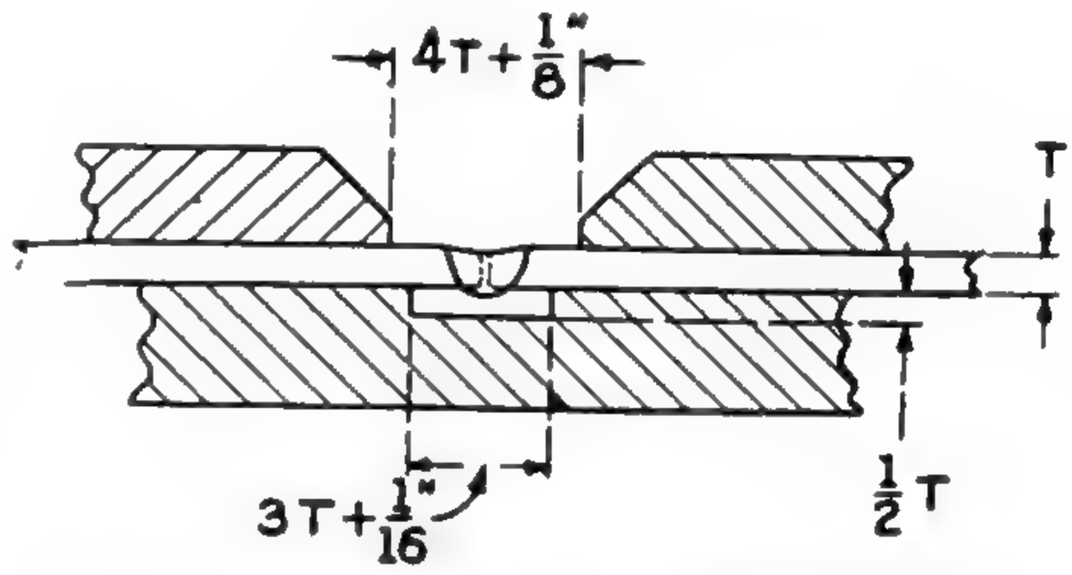

Fig. 1.—Method of Shielding Underside of Weld with Hydrogen

In the selection of welding current, consideration must be given to the requirements of the weld and to the experience or ability of the welders. If the weld is long and the parts not very securely held, or the requirements for finished appearance exacting, lower current values must be used. As the experience and ability of the welders increase, higher currents are permissible. Table 1 is a guide to the selection of the proper values of current as well as electrode extensions.

While the greatest concentration of heat on the seam occurs when the arc fan is vertical and in line with the seam, better heat distribution in the metal adjoining the weld is obtained with the arc fan at an angle to the seam. This angle varies from practically zero for material less than $^1/_{16}$ in. thick to about 30° for material over $^3/_8$ in. thick. To increase the ease of manipulation when filler metal is to be added, the arc fan is frequently inclined slightly from the vertical and away from the side from which the filler metal is to be inserted.

Although welded joints can be made in the vertical or overhead positions with this process, the welding operation is per-

formed so much easier and faster in the flat position that it usually is desirable to arrange to position each joint for flat position welding if possible. The atomic-hydrogen arc renders the molten weld metal so fluid that it runs out of vertical or overhead joints unless the pool is kept quite small and the arc removed to let the weld metal chill at very frequent intervals. Vertical or overhead welding of heavy sections is difficult, if not impossible. The welding of all of the usual types of joint is readily accomplished manually. Machine welding of other than butt joints is seldom if ever done. References below to other than butt joints are for manual welding.

Welds in edge joints are the easiest to make with the atomic-hydrogen welding process. The arc fan is held nearly parallel with the seam, and practically vertical. Penetration is satisfactory when the molten pool flows to the outer edges of the plate and is well rounded. The welders should learn to use this action of the molten metal as a guide in welding edge joints.

Corner joints are quite similar to edge joints and are almost as easy to make. Satisfactory penetration is judged in about the same way, that is, the width of the weld bead should be about equal to the thickness of both plates being welded.

Butt joints can usually be welded without beveling the edges of the joint, for material $^{3}/_{16}$ in. or less in thickness. The conditions encountered are best explained by example. For instance, with $^{1}/_{8}$-in. plate, 100% penetration can be secured because surface tension is strong enough to support the weight of the molten pool obtained with such a thin section. On the other hand, with $^{1}/_{4}$-in. plate, surface tension of the molten metal is not great enough to support the size of the pool required for 100% penetration; hence, beveled edges are required. The thickness above which beveled edges are needed is approximately $^{3}/_{16}$ inch.

In butt welding material which does not require beveled edges, satisfactory penetration is judged by observing the width of the bead and the action of the molten pool. When the surface of the weld first becomes molten, the pool is very active. As the heat penetrates into the metal, the activity slows down until the surface is almost flat. The presence of this condition, combined with a bead width of about three times the plate thickness, indicates complete penetration.

With beveled edges, the root of the joint is sealed, after which filler metal is added to fill the groove completely. This operation does not require multiple passes, as the welder may perform both of these functions simultaneously in a single pass.

Whenever practical, it is desirable in making butt joints to use a backing such as previously mentioned (see Fig. 1), as complete penetration can be obtained more easily and with less danger of molten metal falling through. This also permits the use of higher currents, and faster welding speeds can be realized.

Fillet welds in lap or T joints are not especially difficult, if fit-up is good and if the weld is made in the flat position. This may be accomplished by clamping or tack-welding the pieces together and propping them in position or by use of a jig or positioning table. Good fillet welds are easier to make in the flat position because gravity aids the fluid weld metal to flow into place without leaving undercut areas.

When fillet welds are made in the horizontal position, extra care must be used to produce a deposit of the proper shape without undercut. In the case of a lap joint made in the horizontal position, the heat is applied mostly to the lower plate, applying just enough on the top plate to cause it to flow into the molten pool. Filler metal, if used, should be added so that it flows from the upper to the lower plate. The plates should be fitted as closely as possible to facilitate the flow of metal to the lower plate. With thin metal, a clamp or weight may be necessary to keep the plates in contact.

Weld Properties

The quality of the welding obtained by the atomic hydrogen welding process is excellent when applied by competent welders. The weld metal possesses a fine homogeneous structure, characterized by high ductility. Because of the reducing action of the hydrogen and the highly fluid condition of the molten metal, oxides and other inclusions are practically eliminated from the weld area, giving much cleaner weld metal than is usual with other arc and gas welding processes.

Material that is relatively free from non-metallic inclusions must be used if

the weld is to be free of porosity. As a rule finely divided inclusions are not harmful, but large inclusions, particularly in ferrous alloys, are likely to result in porosity at, or near, the line of fusion.

The process is particularly adaptable to the high chromium-nickel alloy steels, generally known as stainless steels. Welds produced in these alloys have a high corrosion resistance, high tensile strength, good ductility and excellent fatigue resistance. Corrosion resistance of the heat-affected area is less than secured with the inert-gas metal-arc and shielded metal-arc welding processes but greater than obtained with the oxy-acetylene or oxy-hydrogen processes.

EQUIPMENT USED

General

Equipment used in this process consists of three principal parts (see Fig. 2) as follows:

1. A transformer, or other means of converting the power supply voltage to a voltage suitable for welding, and a means for controlling current values.
2. A means for holding the electrodes in position, for supplying a low velocity hydrogen atmosphere around the electrodes and for moving the electrodes to establish and maintain the arc. In manual welding, an electrode holder is used for this purpose, while in machine welding, a welding head and arc control system fulfill this function.
3. A source of hydrogen gas or substitute. Dissociated ammonia is frequently used as a substitute.

Alternating current is commonly used for several reasons. It is available in practically every manufacturing plant. It is readily converted from the supply voltage to the voltage necessary for welding. The two electrodes between which the arc is maintained will be consumed equally when alternating current is used, while, with direct current, one electrode will be consumed at a higher rate than the other, because of the greater amount of heat generated at the positive electrode.

However, direct current is used on occasions. For instance, one application involves the welding of very light gage steel wherein a magnetic field is established across the joint and, because of the lower permeability across the gap, fringes around the joint, and interlocks with the direct current of the arc in such a manner as to accurately center the arc stream on the seam.

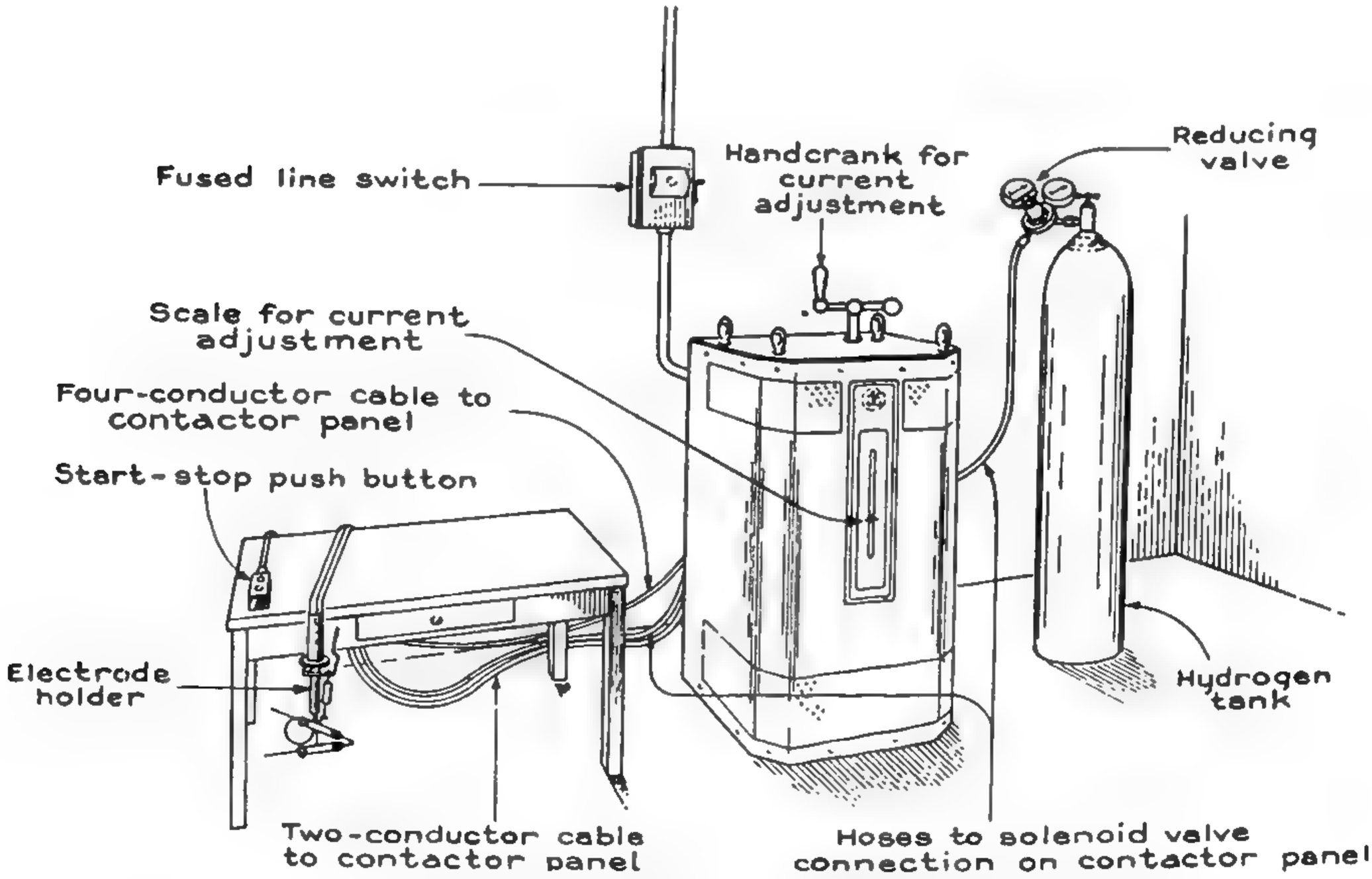

Fig. 2.—Equipment for Manual Welding

The following are needed for controlling and establishing the arc:

1. A means of insulating the welding current from the supply circuit.
2. A reactance or other means of varying the welding current over a suitable range for different applications.
3. A system of contactors to enable the establishment and maintenance of the arc with relative ease and to minimize the possibility of shock to the operator. With the high open-circuit voltage necessary to establish and maintain the arc (300 volts a.c., or 250 volts d.c.), equipment not providing these controls should be avoided.

The methods of accomplishing these functions with alternating current apparatus differ in detail, but follow the same general scheme. The primary of the transformer is connected to the power supply through a fused line switch. The secondary is connected to the welding circuit through a contactor which is held closed while the welding current is flowing but opens if the arc is broken. The welding circuit consists of an ammeter, the electrode holder and a variable reactance which may be included in the transformer as leakage reactance.

When the welding current is low, ease in starting is obtained by increasing the current during the starting period. This has been accomplished in a number of ways, all of which are utilized in equipment now in service.

In the latest type of equipment, where the reactance is incorporated as leakage reactance, the transformer is provided with a fixed core but with a movable primary and a fixed secondary coil, so that the relative location of the primary and secondary windings determines the value of the welding current. A tertiary winding, connected into the circuit during the starting period, provides for the increased current during the starting period. Current adjustment is obtained by rotating a handwheel, moving the coil to the desired position which is indicated by a pointer moving on a vertical scale calibrated in amperes so that current adjustment may be made either with or without the arc being estabished.

Hydrogen is commercially available in tanks or cylinders, or a mixture of hydrogen and nitrogen may be obtained by the use of an ammonia dissociator. A pressure regulator is required for maintaining a constant low pressure of hydrogen, and a solenoid valve, arranged to permit hydrogen flow only when welding, is desirable.

Manual Equipment

For manual welding, the equipment includes the power unit and source of hydrogen described in the preceding section (Fig. 2) and an electrode holder (Fig. 3).

The electrode holder not only provides a means for establishing and maintaining the arc but also provides a means for directing the stream of hydrogen with which the arc is enveloped (see Fig. 3). It consists of two tubes molded in a composition handle through which both hydrogen and current flow. The current connection to these tubes is made at the rear of the handle, and is connected to the power control unit through a 2-con-

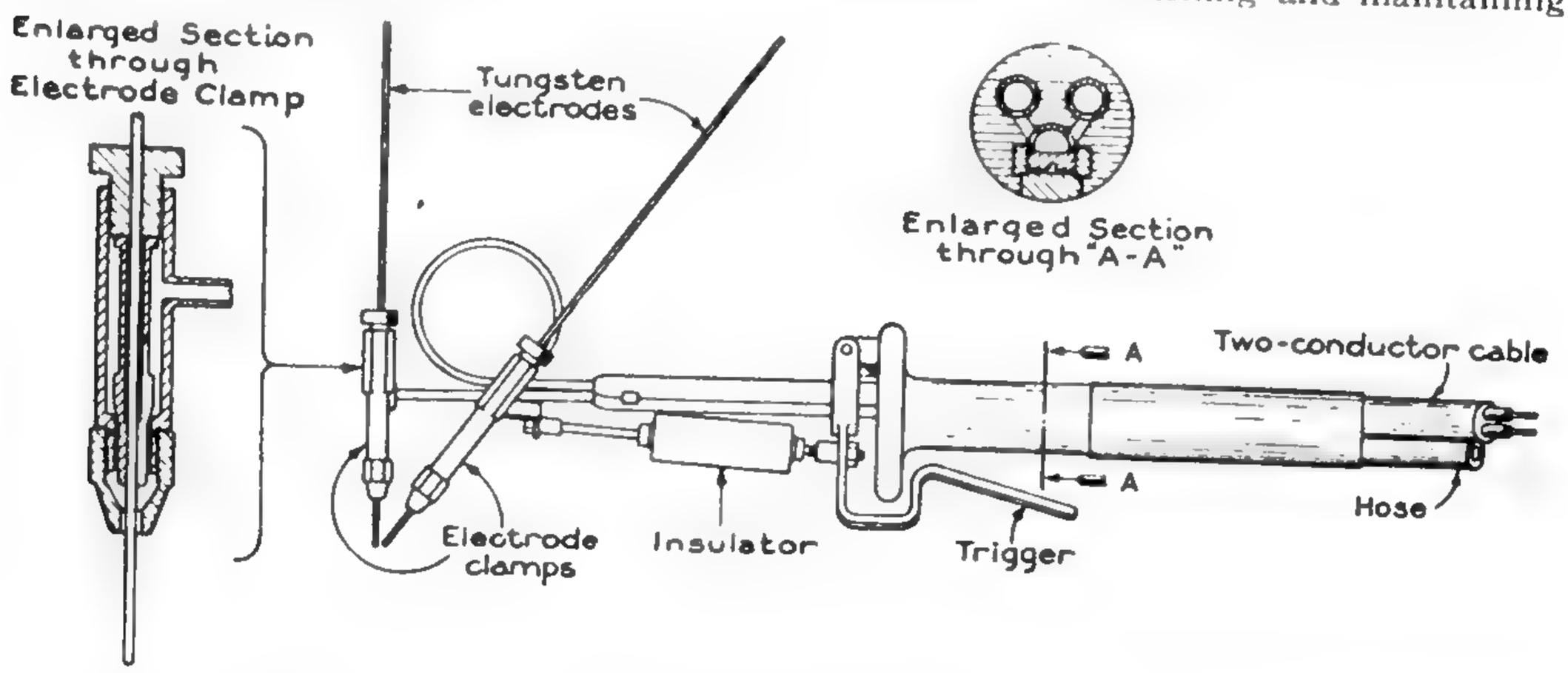

Fig. 3.—Electrode Holder

ductor, flexible cable. The hydrogen is supplied through a hose to a single tube at the rear of the holder from which it is led into the two current-carrying tubes by means of an insulated manifold in the molded handle. Both hydrogen and current are carried to the forward end of the electrode holder on which are mounted the electrode clamps. One of the electrode clamps is movable but is held in approximate position by a coil in the tubing and manipulation is through an insulated connection to the trigger. The coiled tube should be kept from the heat as much as possible to prevent annealing and destruction of its spring action.

If dissociated ammonia is used as a substitute for hydrogen, special tips should be obtained or the hydrogen tips changed to increase the diameter of the orifice 15%.

The electrode holder is usually furnished in one of three ratings, 50, 75 or 100 amperes. The 50-amp. size may be equipped with interchangeable clamps and tips for use with either 0.040-in., $^1/_{16}$-in. or $^3/_{32}$-in. diam. electrodes. The 75-amp. size may be similarly equipped for either $^3/_{32}$-in. or $^1/_8$-in. electrodes and the 100-amp. size for either $^1/_8$-in. or $^5/_{32}$-in. electrodes.

Selection of the electrode size is made according to the welding current used. Each size of electrode should be used with the electrode holder equipped with the proper electrode clamp (see Table I).

not provided with vertical and cross-seam adjustments, these must be included in the welding fixture. A motor, operating through a gear train, drives the electrodes in one direction or the other as required to maintain a constant arc voltage. Hydrogen is fed to a nozzle which guides the electrodes and causes the gas to be properly distributed around them. Portions of the head subjected to the heat of the arc are water-cooled. An adjustment is provided for offsetting the electrodes so as to stabilize the arc. With the proper offset the magnetic effect of the welding current causes the plane of the fan-shaped arc to rotate to a position approximately at right angles to the plane of the electrodes (see Fig. 4). If this offset adjustment is incorrect the fan may oscillate between this position and that normally assumed in manual welding, resulting in non-uniform penetration.

When a greater production rate is required than can be obtained by a single arc, additional units may be installed, or the required number of arcs may be incorporated in a single welding head. While the number of installations of multiple-arc units is small and experience with their use necessarily limited, it may be stated generally that this method has the advantages of broadening the field of application to include heavier material and of lowering the cost per unit length of weld. The improvement in cost is largely due to lower rates of consumption per arc of both hydrogen and tungsten.

Table 1—Current Range and Electrode Extension

Current range, amp.	15–25	15–35	15–50	25–75	60–150
Electrode diameter, in.	0.040	$^1/_{16}$	$^3/_{32}$	$^1/_8$	$^5/_{32}$
Maximum electrode extension, in.	$^3/_4$	$^7/_8$	$^7/_8$	$1^1/_8$	$1^1/_8$
Minimum electrode extension, in.	$^3/_8$	$^1/_2$	$^1/_2$	$^5/_8$	$^5/_8$

NOTE: Electrode extension is measured from the lower face of the hydrogen tip to the arcing end of the electrode.

Machine Equipment

The equipment required for machine welding, includes the power unit and source of hydrogen described in a previous section, a welding head and control for establishing and maintaining the arc (instead of an electrode holder) and a welding fixture or machine for providing relative motion between the work and the arc.

The welding head is arranged for mounting on the welding fixture and, if

The function of the arc control panel is to furnish impulses to the electrode-driving motor, causing it to move the electrodes so as to establish and maintain the arc at a uniform, predetermined voltage. The principal unit in this panel is the voltage-sensitive device which furnishes the impulses to the electrode motor. This may consist of a voltage relay, the coil of which, in series with a regulating rheostat, is connected to the electrode terminals. Recently, thyratron

tubes have been used to perform this function. Such a control system is responsive to very small changes in arc voltage and can be arranged to furnish feeding speeds proportional to the variation of the arc voltage from normal. The result is that the arc voltage can be held within much closer limits than with a system which contains moving mechanical parts.

Fig. 4.—Types of Atomic Hydrogen Arc

The angle between the seam and the fan-shaped arc is determined by the mounting of the welding head, which, as a rule, is such as to make the arc fan and the seam parallel. This may be altered slightly by a change in the offset adjustment, when required to stabilize the position of the arc fan at various values of welding current.

Machine welding is limited almost entirely to comparatively long straight seams in formed plate and to seams having a contour which can be followed readily by automatic displacement of the welding head. The uniformity of conditions provided by automatic control as compared to manual welding makes possible the use of higher values of welding current with a corresponding increase in the welding speed. Fullest advantage of these conditions can be realized only if the seam preparation is also uniform.

The technique used is essentially as outlined for manual welding. As a rule, values of current, arc voltage, speed, and height of the arc above the work are determined by welding sample sections and are not changed during welding. The arc voltage, being automatically controlled, determines the size of the fan-shaped arc which remains constant for the length of the weld. The welding fixture is designed to hold the distance between the arc and the work constant. These two factors are interrelated, as a decrease in the size of the arc raises the fringe and has the equivalent effect of raising the head.

The actual form of the welding fixture will depend entirely on the work to be done. Briefly, it will provide for clamping and holding the work in position and for moving the arc along the seam or for moving the work under the arc. Uniformity of all welding conditions, including alignment and fit of the seam, largely determine the success of machine welding. These points should be given particular consideration in the design of the welding fixture, as any compromise is likely to result in lower welding speeds, a higher percentage of rejects or both.

Auxiliary Equipment

Auxiliary equipment includes all items necessary or useful in the application of the process except the transformer or other means of providing welding current.

Several of these items have been treated in previous sections. The source of hydrogen gas and a substitute have been described under General Equipment. An automatic welding head has been described under Machine Equipment. The most commonly used electrode holder has been fully described under Manual Equipment. However, certain applications may require a modification or a specially designed electrode holder. Figure 5 is an illustration of an electrode holder especially designed for relatively low welding current values, light weight and greater ease in manipulation.

Tungsten electrodes are available in a

range of diameters from 0.040 to $^{3}/_{16}$ in. nominal sizes being in 32nds of an inch. For manual welding, 12-in. lengths are usual, and may be used for machine welding in diameters up to $^{1}/_{8}$ inch. In the larger diameters, lengths of 2 to 5 ft. result in some economy in machine welding.

Jigs or fixtures for positioning the work are very useful in manual welding of a repetitive nature and are essential for machine welding. If possible, such fixtures should hold the parts to be welded in secure alignment. Particularly for machine welding, it is desirable to provide water cooling for the parts which hold the seam in alignment and control the heat flow away from the weld. Proper attention to this feature will reduce distortion and the extent of the heat-affected zone to a minimum. In stainless steels, the extent of carbide precipitation also is reduced.

A helmet, such as is used in other arc-welding processes, or partial glass screening is necessary to protect the welders from the light of the arc. To protect other workers, it is desirable to provide movable or fixed screening of canvas or light sheet metal.

Other accessories include scratch brushes, pliers, and an assortment of clamps, angles, etc., for positioning and clamping.

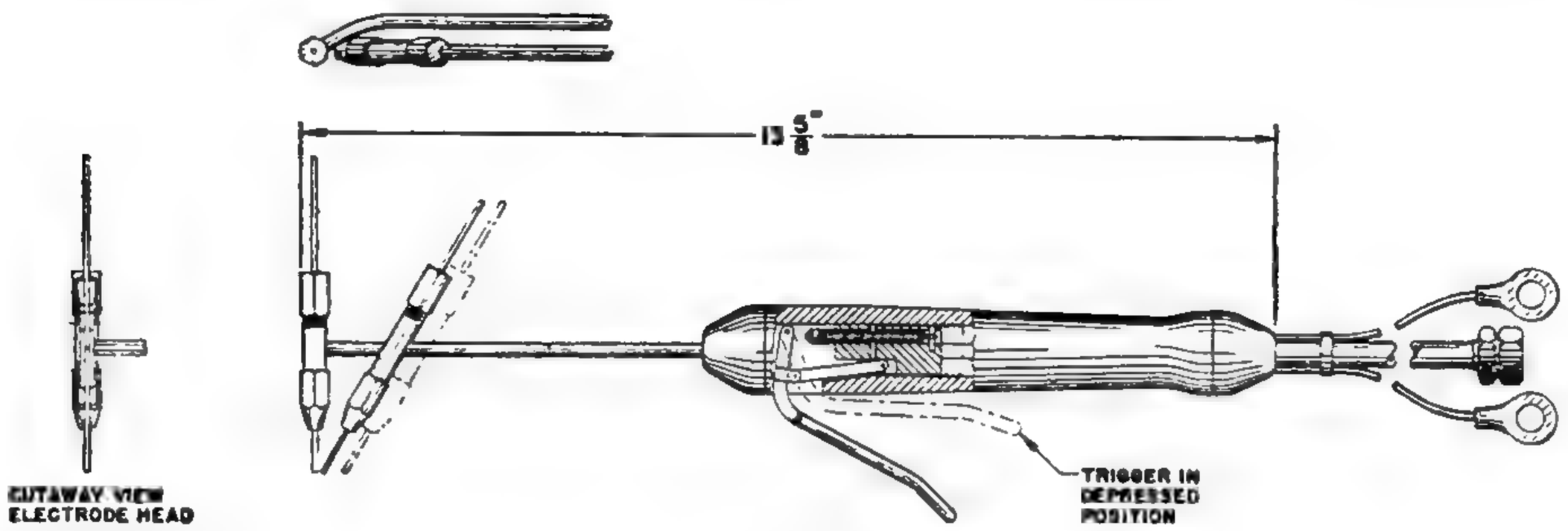

Fig. 5.—Special Electrode Holder

METHODS AND TECHNIQUE

General

The factors which constitute welding technique are grouped generally into two classes: adjustments for the equipment and manipulation. These factors are interrelated, and as the operator's skill in manipulation increases, a change in the equipment adjustments is perfectly logical. For this reason, strict adherence to the following current adjustments is not recommended.

The method of current adjustment has been described in a previous paragraph. This adjustment should be made to provide the proper welding current as dictated by the particular application. (Table 2, Machine Welding Data, or Table 3, Manual Welding Data.)

Table 2—Machine Welding Data

Thickness, In.	Welding Current, Amp.	Voltage	Welding Speed, In./Min.	Consumption Rates Power, Kw.	Hydrogen, Cu. Ft./Hr.		Electrode In./Hr.
0.015	35	50	140	3.2	60	1.2	$^{1}/_{16}$ diam.
0.025	45	55	80	2.9	80	2.2	
0.035	50	60	65	3.5	90	0.8	
0.050	60	63	50	4.5	100	1.3	$^{3}/_{32}$ diam.
0.065	68	65	37	5.2	110	2.2	
0.078	75	65	30	5.6	120	3.0	
0.094	83	68	22	6.5	120	1.5	
0.109	87	68	18	7.0	120	1.8	$^{1}/_{8}$ diam.
0.125	95	70	16	7.6	120	2.0	
0.141	100	70	14	8.1	120	1.2	
$^{5}/_{32}$	105	72	12	8.6	120	1.5	
$^{3}/_{16}$	110	72	10	9.2	120	1.7	$^{3}/_{16}$ diam.
$^{1}/_{4}$	120	75	7	10.2	120	1.8	
$^{5}/_{16}$	130	75	5	11.0	120	1.9	

The electrodes should be adjusted to the maximum extension given in Table 1 before starting to weld. They are slowly consumed during welding and should be readjusted when they have reached the minimum extension. After the electrodes have been inserted, the clamp should be tightened only enough to hold them snugly. This allows adjustment of the electrodes by tapping lightly with a wooden or fiber block.

The angle between the electrode clamps should be such that, with the trigger free, the electrodes will be in contact when extending 1/8 in. less than the minimum values given in Table 1.

The travel of the movable electrode can be adjusted by means of the insulated turnbuckle connecting it with the trigger. This adjustment should be such that, with the trigger free and the electrodes extending 1/8 in. less than the minimum distance, they will touch. With the trigger pressed against the handle and the electrodes extending the maximum distance, they should be about 3/8 in. apart.

The adjustment of hydrogen flow should receive careful consideration. A poor adjustment affects the welding speed or quality and causes either excessive hydrogen consumption or excessive tungsten consumption. Having selected the proper electrode holder and electrodes, the current should be set for the highest value to be used with the electrode size selected (see Table 1). With the hydrogen reducing valve set at about 10 psi., strike and maintain the arc as described below. Reduce the pressure until small beads, indicating insufficient cooling and rapid tungsten loss, begin to form on the ends of the electrodes and the well-defined arc disappears. Increase the pressure until the beads no longer form and a well-defined arc is obtained. Observe the gage reading under these conditions, which will be between 4 and 7 psi. and keep the reducing valve set at this point unless the electrode holder is changed. A different electrode holder, of the same or a different size, may require a different setting.

Reducing valves vary as to the minimum point at which they will hold pressure accurately. That required by the electrode holder is slightly less than 1 psi., but the throttling action of the solenoid valve may be adjusted so that the reducing valve will operate in its range of accuracy. There is an adjusting

Table 3—Manual Welding Data

Welding Speeds in In./Min. for Various Values of Thickness and Joint Types

Thickness, In.	Lap or Tee Speed	Butt Thick., In.	Butt Speed	Corner Thick., In.	Corner Speed	Edge Thick., In.	Edge Speed	Current Range, Amperes	Power, Kw.	Consumption Rates (In./Min.) and Hydrogen (Cu. Ft./Hr.) — Tungsten Electrodes — 0.040 Elect. Electrode Hyd.	0.062 Elect. Electrode Hyd.	0.093 Elect. Electrode Hyd.	0.125 Elect. Electrode Hyd.	0.187 Elect. Electrode Hyd.	Electrode Hyd.
1/32	Difficult	1/32	...	...	...	1/32	11-12	15-20	1.1	0.73	0.55	...	...	...	...
1/16	8-9	1/16	...	1/16	11-13	...	13-14	20-25	1.4	1.14	0.86	...	...	...	...
3/32	7.5-8.5	1/16	9-12	...	...	...	10-11	25-30	1.8	...	1.30	0.66	...	...	...
1/8	7-8	3/32	8-10	1/8	12-13	1/16	12-13	30-35	2.2	...	1.85	0.75	...	...	...
3/16	3.5-4.5	1/8	7-10	3/32	11-12	3/32	11-12	35-40	2.6	...	2.51	0.94	...	...	...
...	...	3/16	3-3.5	1/8	9-10	1/8	...	40-45	3.0	...	...	1.16	...	...	...
1/4	2.5-3.5	1/4	2.5-3	3/16	5.5-6	3/16	4-5	45-50	3.5	...	...	1.42	...	...	...
5/16	2-2.5	5/16	1-1.5	1/4	4-4.5	1/4	3-3.5	50-55	3.9	...	...	1.72	...	...	...
...	...	1/4	...	5/16	2.5-3.5	5/16	2-3	55-60	4.4	...	...	2.04	...	...	...
1/2	1.5-2	5/16	0.75-1	1/2	2-2.5	1/2	1.5-2	60-65	4.9	...	...	...	...	...	...
1/2	2-2.5	...	...	...	...	...	...	70-75	6.0	...	...	...	...	...	...
...	...	1/2	1-1.5	...	2.5-3	1/2	1.75-2.5	75-90	7.1	...	...	...	...	...	...
								90-100	8.5						
								100-120	10.1					90	1.31
								120-140	12.5					90	1.57
								150	15					90	1.94
														90	2.75
														90	3.90

The following speeds apply to all the joints indicated above, for thicknesses of 1/2 in. and greater, and are expressed in cu. in. of welding rod deposited per hour. 6-8, 7-9, 8-10

screw for this purpose on the solenoid valve which is accessible through a hole in the supporting panel between the inlet and outlet connections.

To start the arc, set the reducing valve at about 10 psi. unless the hydrogen adjustment has already been made. Grasp the electrode holder and pull on the trigger until the electrodes are separated. Hold the start button depressed and allow the electrodes to come together and then immediately separate them about $^1/_{16}$ inch. This ignites the hydrogen and starts the arc. If the arc is not started the first time, close and open the electrodes again. The start button should be released as soon as the arc is started. Then adjust the flow of hydrogen as described above. If the electrodes freeze together, depress the stop button and gently force the electrodes apart with a welding rod or pliers, and proceed as before. The electrodes are brittle, and care should be exercised to avoid breakage. Another method frequently used to establish the arc is to separate the electrodes slightly after the hydrogen is ignited and draw them across a piece of charred wood, graphite or metal.

To stop the arc, depress the stop button or increase the gap between the electrodes until the arc breaks. While the arc may be *snuffed out* by bringing the electrodes together, it is poor practice and should be avoided. If this should occur, intentionally or otherwise, the electrodes should be separated by depressing the trigger, or the stop button should be depressed to remove power from the welding circuit, and the electrodes pried apart.

As the work does not form a part of the electrical circuit, the arc may be started with the electrode holder in any position. The majority of experienced welders start the arc with the electrode holder in a vertical position and raised slightly above the head. This allows the helmet to be in the raised position until ready to start actual welding.

The distance between the tips of the electrodes determines the arc voltage and the type and size of the arc stream (Fig. 4). In normal use, the arc stream assumes a fan shape which varies in diameter between $^3/_8$ and $^3/_4$ inch. Under these conditions the arc voltage varies between 50 volts and 90 volts, and the arc produces a singing noise. If the electrodes are brought closer together so as to reduce the diameter of the fan below $^3/_8$ in., the singing noise stops and the fan suddenly disappears, being replaced by a pointed arc extending about $^1/_{16}$ in. beyond the tips of the electrodes, usually called a *silent* arc. In this case the arc voltage ranges between 20 volts and 40 volts.

When the arc stream is viewed through a welding glass, it is seen as a very definite circular outline having very little depth and normally lying in a plane substantially the same as that of the electrodes (see Fig. 4). This is the normal position, that is, the electrodes lie in exactly the same plane. However, the electrodes can be offset to rotate the fan to a position approximately at right angles to the plane of the electrodes. In this position the electrodes lie in two parallel and slightly separated planes. While an adjustment is provided for this purpose on the automatic head, no such means is provided on the electrode holder. If it is desired to permanently displace the arc fan to the right-angle position, the spring loop may be gently forced into the desired position, but frequent changes of this nature are not recommended and may result in permanent injury to or destruction of the electrode holder.

The greatest concentration of atomic hydrogen occurs at the outer boundary or fringe, and this edge should just touch the surface to be welded. Holding the arc higher than this spreads the heat over a larger area and is useful for preheating or for finishing off the end of the weld. If the arc is held too low, heat is inefficiently distributed and the electrodes will be contaminated unnecessarily by spatter from the weld which lowers their melting point, and causes excessive consumption.

Spatter will accumulate on the tungsten electrodes and on the tips through which hydrogen gas flows. That which adheres to the electrodes will later alloy with the tungsten and that which adheres to the tips will cause poor gas distribution. A wire brush is effective in removing a lightly adhering spatter, and if used frequently will usually be all that is required. A dull-edged tool such as a screw driver or file prong may be used to remove tightly adhering spatter. Failure to remove this spatter will result in excessive tungsten consumption and may influence adversely the speed and quality of welding.

Filler rod is added by creating a liquid surface or molten pool, depending on the penetration required, adding to it drops of liquid metal melted from a rod or bar of the desired composition, and fusing thoroughly and quickly. As a general rule, it is better to melt the end of the rod by intermittently inserting it in the forward fringe of the arc fan. The added metal is fused as the arc moves forward to continue the weld.

When adding filler metal, extra care must be taken to prevent contamination of the tungsten electrodes by metal from the welding rod or pool. The alloy thus formed has a lower melting point than tungsten, and a molten ball usually forms on the end of the electrode, causing the arc to be very erratic. The disturbing alloy will disappear if the arc is maintained for a sufficient length of time but may be quickly removed by rapidly moving the electrode holder up and down with the arc established. This causes the hydrogen to be temporarily displaced, allowing the air to oxidize the alloy very quickly. Another practice is to stop the arc and break off the disturbing alloy with pliers.

The nature of the work governs the selection of the welding current, and the size of the fan-shaped arc. For thin metals and small parts the lower currents are used with a small arc fan or a *silent* arc. Both the current and size of the arc fan increase with the size of the work.

The use of filler metal depends on the desired finished appearance, and thickness and type of work being done. In the case of butt welds where the thickness exceeds $^{3}/_{16}$ in., it is necessary to bevel the edges in order to obtain uniform and complete penetration and to add filler metal to supply the metal to fill the groove. All fillet welds require filler metal, and it is frequently required in the other types of welds.

Since the atomic-hydrogen arc transfers heat into the work very rapidly, the arc should not be held in one spot too long, otherwise the metal may be overheated locally, with the possible loss by vaporization of important alloying elements. A second precaution is that the fringe of the arc should not be held away from the surface of the work more than about $^{1}/_{8}$ in., otherwise the hydrogen may not completely envelop the molten metal, and surface oxidation may occur.

Selection of Filler Metal

In selecting a welding rod, best results will be obtained if the diameter is proper for the thickness of work being welded. With light work, requiring up to 25 or 30 amp., a diameter of $^{1}/_{16}$ or $^{3}/_{32}$ in. is ordinarily used. When a large addition of filler material is required, as with heavier work, the diameter may be increased up to $^{1}/_{4}$ in. with currents up to 150 amperes.

The analysis of the filler metal for alloy steels should be practically the same as that of the parent material, except for carbon content which should be about one-third greater to compensate for loss of this element during welding. Of course, if the pool of weld metal is kept in a molten condition longer than normally required for good fusion, as may be necessary when welding heavy sections, or if the metal is overheated, the loss of carbon tends to increase, for which further allowance may need to be made. The loss of other alloying ingredients is negligible, unless the arc is held so long in one place that serious overheating occurs.

When it is necessary to obtain filler metal by cutting it from a piece of a bar or a die, it is best done by band saw. Care should be taken to obtain clean metal, and to prevent decarburized steel from getting into the weld.

Alloy Steels

Alloy steels may be welded in virtually the same way as mild steel. Less welding current is ordinarily required, especially with steels having a high alloying content, such as stainless steels. In this work, a perfect weld is much more important than time, so no attempt is made to achieve speed in welding. The welders handling this work must have unusually keen knowledge of all the factors involved and the great success obtained in this field is largely a result of their technique and experience.

To prevent cracking in the high-carbon, air-hardening, and oil-hardening alloy steels, the pieces to be welded generally should be carefully annealed before and after welding. However, it is possible in some cases to weld without annealing. If there is any doubt it is best to be on the safe side and anneal a piece before it is to be welded. In some welding operations there are slight distortions. These pieces can nearly always be straightened by using pressure while the part is at a

red heat. If straightening is not possible, sufficient metal should be deposited so that the repaired part can be remachined to the proper size. Tools which have been repaired should be hardened in the same manner as is recommended for tools of the same type that have not been welded.

In repairing molds and dies, the addition of small amounts of filler metal to a comparatively large mass of base metal is a frequent requirement. Such work usually requires special precautions in order to obtain the proper heat distribution, particularly throughout the metal adjacent to the weld area. Proper heat distribution can be obtained by preheating, a procedure which is recommended on all but very small pieces weighing two pounds or less. Even such small pieces should be preheated (with the arc if convenient), until they are barely comfortable to touch, before welding is begun. Larger pieces require more preheating, and a piece weighing 50 lb. or more, or 2 in. in thickness, should be heated to a dull-red temperature before welding. Usually it is better to preheat larger pieces in a furnace or with a gas torch. To obtain further good heat distribution, the metal should be brought to the melting point slowly during welding, in order to avoid porosity.

In most work of this kind, alloy steels are involved, which means that the filler metal used should be carefully selected, as outlined in the preceding section. In adding the welding rod, the arc is played upon the work until a spot upon the surface becomes molten, whereupon the end of the rod is melted into this surface pool. The rod is then withdrawn and the deposited metal is fused into the surface of the base metal by playing the arc around the edge of the droplet until it flows into the surface.

COMMON APPLICATIONS

General

Atomic hydrogen welding is applicable to practically all the nonferrous as well as ferrous metals and alloys. Flux is required in the welding of aluminum, or copper and copper alloys, and often is useful in welding the various types of stainless steel. Flux for all of these materials is readily obtainable and selection is largely a matter of individual choice. As a general rule all such metals and alloys should be preheated and lower values of welding current used than with similar masses of steel.

In the repair of steel molds and dies the atomic-hydrogen process has been very widely used with outstanding success. Deposited metal is sound and dense, and by proper selection of filler material, can be made to duplicate almost exactly the properties of the base metal. The rapid heating and controllable depth of fusion afforded by this process facilitate the building-up of worn or spalled surfaces and the correction of errors in machining with a minimum of disturbance of the parent metal.

In the fabrication of thin stock, particularly where the joint can be prepared in such a way as to require no addition of filler metal, atomic-hydrogen welding finds a broad field. Automatic welding heads are widely used in the production of tubing made of alloy steels, including the 18 8 steels, chromium, chromium-aluminum and SAE 4130 steel, as well as Inconel. Typical applications include the fabrication of nickel and Monel tanks, float balls, aluminum parts, aircraft propellers, capillary tubes for instruments and heavy-walled tubing for automotive rear-axle housings (see Table 4).

While operating costs of the atomic hydrogen welding process are not quite as

Table 4—Typical Applications for Atomic Hydrogen Welding

Material	Thickness Range, In.	Product
Stainless steels	0.025–0.150	Aircraft superchargers, manifolds, etc. (Fig. 6)
Steel (medium carbon)	0.250–0.330	Automotive tubing
Stainless steel	0.025–0.125	Beverage tubing
Stainless steel	0.037–0.050	Beer barrel liner
Stainless steel	0.031–0.050	Dairy machinery tubing (see Fig. 7)
Silicon steel	0.010–0.015	Electrical magnetic strip
Inconel	0.025–0.035	Home-appliances—tubing
Monel	0.045–0.093	Home appliances—hot water tanks
Steel (mild)	0.035	Cartridge magazines
Steel (medium carbon and stainless)	0.078–0.156	Hollow spheres
Stainless steel	0.025–0.065	Oxygen tanks (see Fig. 8)
Alloy steels	....	Sheet-metal forming—die repairs

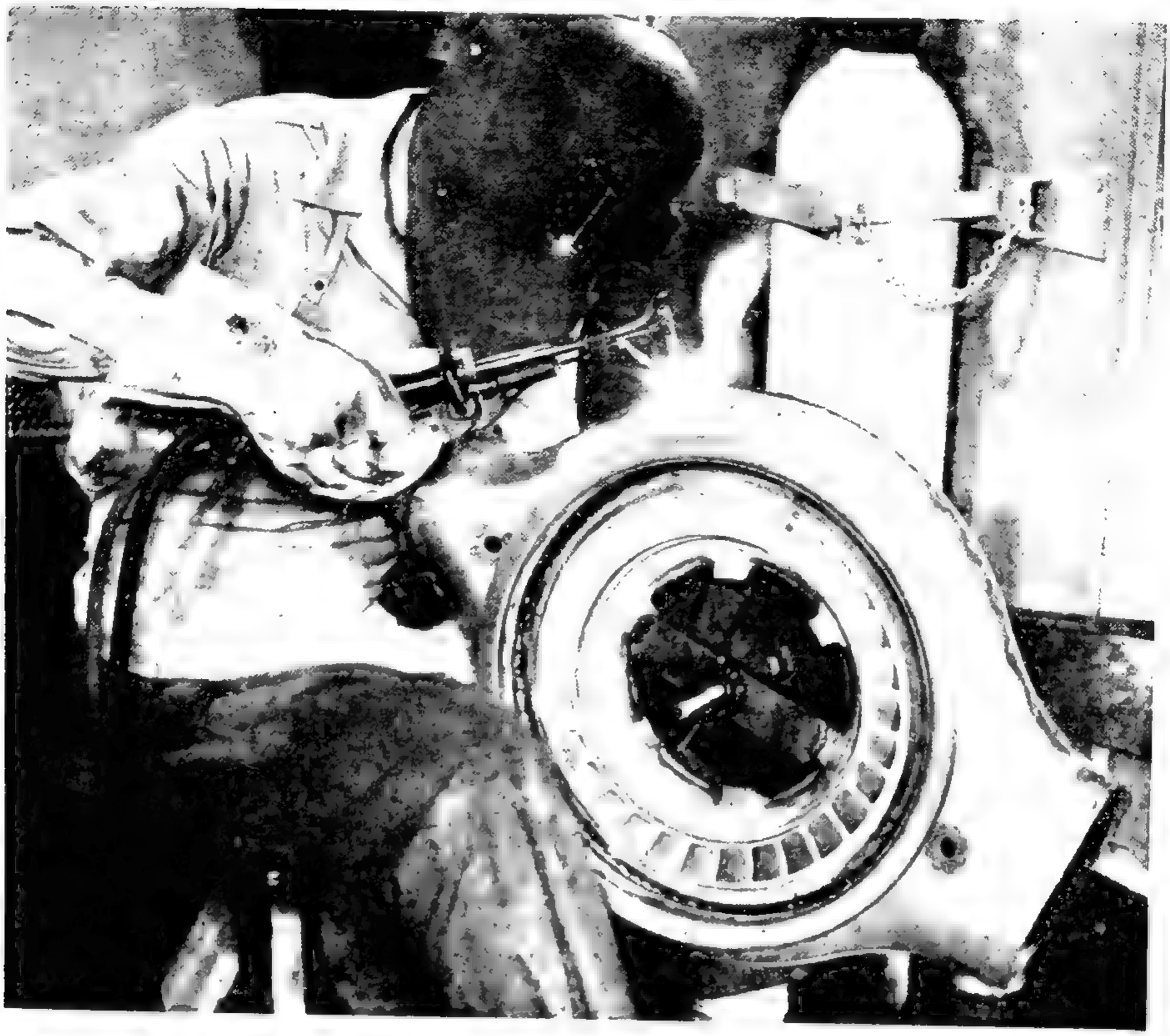

Fig. 6.—Example of Manual Atomic Hydrogen Welding
Stainless steel nozzle box for aircraft superheater

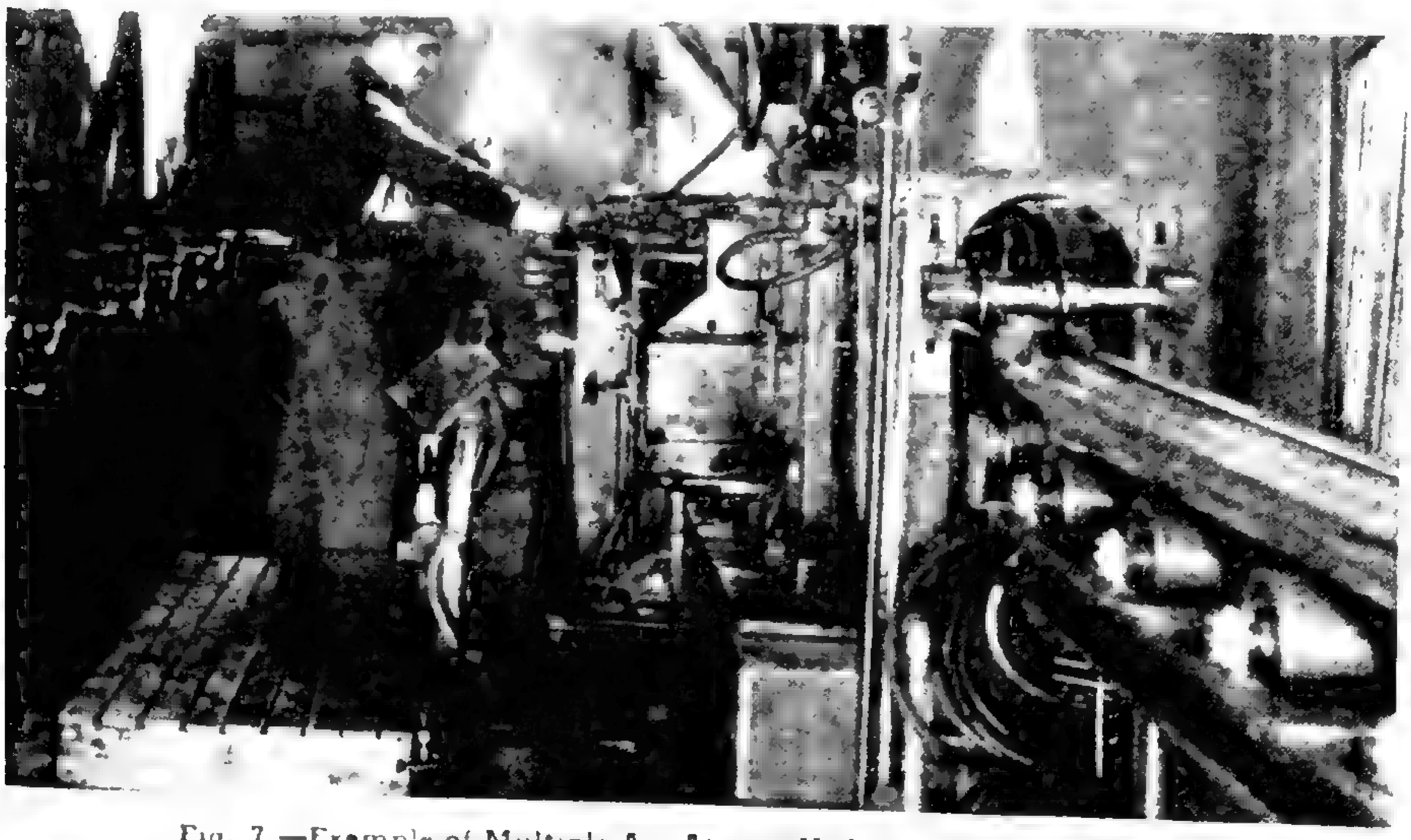

Fig. 7.—Example of Multiple Arc Atomic Hydrogen Machine Welding
Installation for welding steel tubes [illegible] 33 mm wall thickness, 6 m OD approx

low as those of the conventional arc welding process, nevertheless it is found that atomic hydrogen welding can be used for work which cannot be done so successfully by other means. Thus, it affords additional opportunities to save time, money and material in the manufacture of production parts and in the repair and maintenance of equipment, particularly the repair of tools and dies.

The process has demonstrated its ability to make tremendous savings because of the ease and speed with which worn parts may be rebuilt and likewise the ease with which filler metal can be obtained. Filler metal can frequently be obtained from scraps of the base material or possibly cut from the work piece itself. This is a particularly attractive feature of the process in that practically any of the commonly used base metals can be welded. Also, because of the ease of obtaining filler metal, it is ideal for repairing special ferrous alloys such as chromium, nickel and molybdenum steels as well as the nonferrous alloys.

Welding Data

The overall welding time, as the term is generally used, includes the time necessary to set up the parts for the welding operation, as well as the time consumed in welding. The setup time varies over a wide range and depends not only on the variety of work being welded but on the design of the parts, accuracy of the preceding workmanship and the facilities available for making a proper setup. It is frequently computed as a percentage of the welding time. In the data given in the tables this is not included, welding speeds being based on the time necessary to make the weld, usually called *arc time.*

The data for manual welding are given in Table 3. In using these data for computing welding time, the length of the seam should be increased to compensate for the time required to start and finish the weld and for intermediate pauses. A fairly accurate value is 1 in. plus an additional inch for each 2 ft. of length.

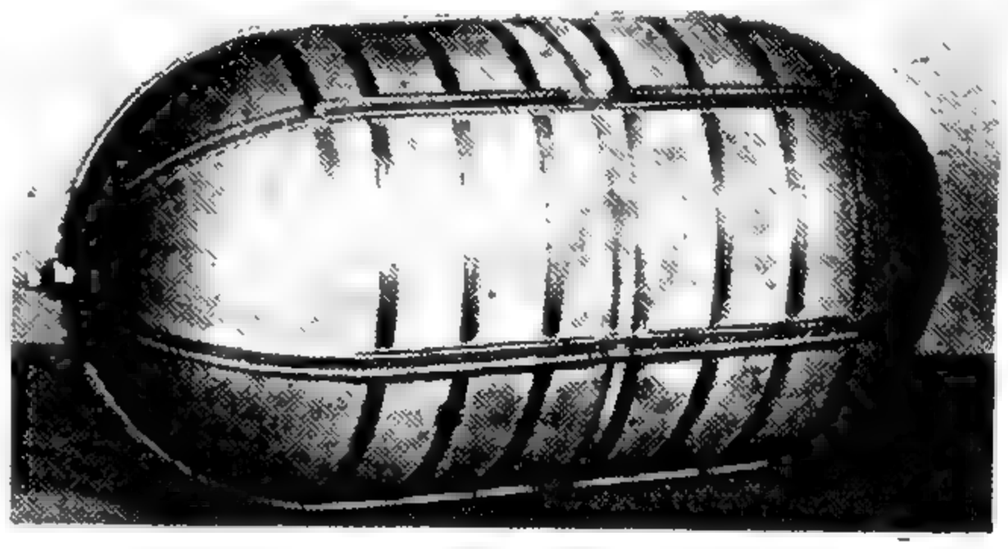

Fig. 8.—Single Arc Machine Welding.
Oxygen container of stainless steel with welded girth seam and fittings.

For automatic or machine welding, data are available for butt joints only (see Table 2), as other joint types are seldom used. Material having a thickness in excess of $^{3}/_{16}$ in. is seldom machine welded. When it is, the joint must be properly backed to avoid spill-through or some equally effective method provided. For very thin material, magnetic stabilization of position of the arc is necessary. For computing welding time, the data from Table 2 should be used, noting that a much higher duty factor is usually obtained, and that no addition for the start and finish of the weld is necessary.

BIBLIOGRAPHY

1. *Atomic Hydrogen Arc Welding,* R. A. Weinman and I. Langmuir, General Electric Review, March 1926.
2. *Flames of Atomic Hydrogen,* I. Langmuir, Western Society of Engineers Journal, October 1926; Power Plant Engineering, Oct. 15, 1926; General Electric Review, March 1926.
3. *Welding With the Atomic Hydrogen Flame,* R. A. Weinman, The Welding Journal, October 1926.
4. *Recent Developments in Atomic Hydrogen Welding of Alloys,* P. P. Alexander, Iron Age, April 4, 1929; Electrical Railway Journal, May 1929.
5. *Welding of Ferrous and Non-Ferrous Metals by the Atomic Hydrogen Flame,* R. A. Weinman, General Electric Review, October 1929.
6. *Automatic Arc Welding with Atomic Hydrogen,* J. T. Catlett, American Machinist, March 15, 1933.
7. *Manufacturing Airplane Struts,* F. L. Prentiss, Iron Age, December 12, 1935.
8. *Dissociation in Arc Welding,* C. G. Suits, Electrical Engineering, May 1936.
9. *Atomic Hydrogen Arc Welding Solves Difficult Problems,* W. E. Wilson, General Electric Review, October 1939.
10. *Automatic Atomic Hydrogen Welding of Steel,* J. T. Catlett, Iron and Steel Engineer, January 1940.
11. *Manual Atomic Hydrogen Welding of Tool Steels,* C. H. Spearman, Steel, May 18, 1942.
12. *Atomic Hydrogen Arc Welding Aids Joining of Thin Sheet in Aircraft Production,* W. J. Van den Akker, Steel, July 17, 1944.
13. *The Atomic Hydrogen Welding Process,* W. P. Brotherton, Steel Processing, August 1946.
14. *Atomic Hydrogen Welding of Stainless Steel,* George Richardson, Iron Age, May 8, 1947.
15. *Effects of Flux in Welding Stainless Steel,* George Richardson, Iron Age, May 1, 1947.

CHAPTER 12

INERT-GAS METAL-ARC WELDING*

FUNDAMENTALS OF PROCESS

Definition and General Description

INERT-GAS METAL-ARC WELDING is an arc-welding process wherein coalescence is produced by heating with an electric arc between a metal electrode and the work. Shielding is obtained from inert gas such as helium or argon. Pressure may or may not be used and filler metal may or may not be used. Tungsten electrodes are generally used because of their higher melting point and with the protection provided by the inert-gas, argon or helium, the electrode is virtually nonconsumable. Filler metal is added to the weld in the same manner as in oxy-acetylene or carbon-arc welding.

The inert gas in conjunction with the proper type of welding current also performs another important function, namely that of a cleaning action, which is beneficial in welding aluminum, magnesium, beryllium copper and some alloys containing additions of aluminum or beryllium which form a refractory oxide. In welding most other metals, this cleaning action plays no significant part

The function of the electrode and weld puddle protection is readily understood because the air is simply displaced physically by the flowing inert gas. Thus the required rate of inert gas flow for any particular welding operation is that rate which will give effective shielding. This flow rate depends upon the size of the molten puddle, type of metal being welded, type of inert gas employed, welding speed and presence of drafts or wind in the vicinity of the welding operation. The rate of gas flow is not determined directly by the heat requirement of the weld since it is not involved directly in the actual heating operation.

Welds can be made in practically all metals without the use of flux. No significant amount of oxides is formed, and therefore fluxes are not required to remove them from the weld zone. With manual equipment, welds can be made in all positions.

Principles of Operation

An electric arc is produced by the passage of an electric current through an ionized gas. In this welding process the inert gas atoms are ionized. They lose electrons and are left with a positive charge. The positive gas ions flow from the positive to the negative pole of the arc; the negative electrons travel from the negative to the positive pole. The power expended in an arc expressed in electrical units is the product of the current passing through the arc and the voltage drop across the arc. The voltage drop across the arc consists of a fixed amount at each arc end and a variable amount proportional to the length of the arc.

It is well established that when the electrode is positive and the work negative the oxide coating on the metal being welded is removed. Several theories have been proposed to explain this action. One of these is that the electron flow from the plate breaks up the oxide layer and disperses it during d.c., reverse polarity welding or during the reverse polarity cycle of a.c. welding. A second theory explains the cleaning action on the basis of ionic bombardment. Positively charged gas ions attracted to the negatively charged work-piece strike the surface with sufficient force to break up and dislodge

* Prepared by a committee consisting of H E. Rockefeller, The Linde Air Products Co., Chairman, G. J. Gibson, Air Reduction Sales Co., H T Herbst, The Linde Air Products Co., G. O Hoglund, Aluminum Company of America; T. R. Lichtenwalter, Republic Steel Corp.; I C Mattson, Dow Chemical Co., T E. Piper, Northrop Aircraft, Inc.; M Rebuffoni, Westinghouse Electric Corp.; E. E Tisza, Air Reduction Sales Co.; R F Wyer, General Electric Co

the oxide layer. This action may be compared to a miniature sandblasting operation. In fact, under the microscope the area of the metal surface adjacent to the weld has the appearance of a sandblasted surface.

A third theory is that metallic ions as well as gas ions help to dislodge this oxide surface and a fourth theory is that an electrolytic dissociation of oxides takes place. Since this cleaning action takes place with flow of reverse polarity current, the metal oxides are dissociated so that the positively charged metal ions are deposited on the negatively charged weld zone. The oxygen so liberated is carried off to either side of the weld zone in the inert gas stream.

The second of these theories appears to be applicable to inert-gas metal-arc welding because the cleaning effect of the two gases, argon and helium, seems to be somewhat in proportion to their atomic weights. The cleaning action with the heavier gas, argon, is much more pronounced than the cleaning action in the case of the relatively light helium, which has an atomic weight of about one-tenth that of argon.

Since this cleaning action plays an important part, principally in welding aluminum and magnesium, the above description applies mainly to these two metals and their alloys. For welding these metals alternating current with superimposed high frequency, alternating current of higher than usual open-circuit voltage or balanced-wave alternating current is used. Direct current, reverse polarity is also used for welding these metals in very thin sections.

For d.c.. reverse polarity welding, the electrode is positive. The negative electrons strike the electrode and heat it. This condition makes necessary the use of a $^1/_4$-in. diam. tungsten electrode to carry 125 amp. for welding up to only $^1/_8$-in. thick aluminum, because electrons heat the electrode instead of the plate. The weld puddle is shallow and wide. Direct current, reverse polarity is not widely used because heating of the electrode is so severe.

In d.c., straight polarity welding the negative electrons are directed to the positive plate at fairly high velocity. The positive gas ions are directed toward the negative electrode at relatively low velocity. As the electrons strike the plate, considerable heat is liberated, thus heating the plate more than the electrode.

Direct current, straight polarity is used for welding practically all metals other than aluminum and magnesium. The main reasons are that the weld puddle is deeper and narrower than in the case of d.c., reverse polarity or alternating current. Therefore, the contraction stresses are less so that less trouble with hot cracking of some metals is encountered. Because the rate of heat input is more rapid with d.c., straight polarity, less distortion in the base metal results. The weld puddle is molten for a shorter time because of the faster rate of heat input with this type of current, and therefore gas reactions have less time to take place. Higher welding speeds are also possible. Greater heat is developed at the positive end of the arc, which is the weld puddle, and considerably less heat is developed at the negative end of the arc, which is the end of the tungsten electrode. Therefore, there is less tendency to heat the electrode and smaller electrodes can be used for a given welding current.

Safety

The safety precautions and protective equipment for metal arc welding are applicable in general to inert-gas metal-arc welding. (See Chapter 46). Welding helmets or full face shields should be used and all areas of the operator's skin which are exposed to direct radiation from the arc should be covered. There is no hot metal or slag spatter with inert-gas metal-arc welding hence there is less danger of clothing fires than with shielded metal-arc welding. However, eye protection is very important and a somewhat darker shade of protective filter glass should be used than for shielded metal-arc welding. Standard arc-welding helmets with lenses ranging in shade from No. 6, for work using up to 30 amp., to No. 14, for work using more than 400 amp., should be used. Use of a glass that is too dark is to be avoided to prevent eyestrain. The upper part of the operator's body should be protected with a closely woven shirt with a tight collar and long sleeves. Light cotton or leather gloves are recommended. Adequate arc shielding should be set up to protect other workers.

The general use of high-frequency-stabilized alternating current requires

special protection. This method of arc stabilization uses frequencies in the radio spectrum and although a potential of 3000 volts is commonly used it is not dangerous from the standpoint of electric shock because the power is low. However if the welder's hands are not protected from the high frequency current it may cause a painful burning sensation at the point of contact and may result in small skin burns which are difficult to heal. Good protection is now provided by adequately insulated electrode holders. The gases used to shield the arc are inert and have a high purity so there is no danger from this source.

EQUIPMENT USED

Inert-gas metal-arc welding has a wide range of application and a large variety of equipment is needed to meet the requirements of all applications. The type and amount of equipment depend on the welding requirements of each job and the number of duplicate pieces to be welded. The absolute minimum essential equipment for manual inert-gas shielded-arc welding consists of (1) a suitable torch or electrode holder for the electrode, (2) a supply of inert gas, (3) a gas regulator and flowmeter, and electrical controls, (4) a source of welding current—a welding generator or transformer, (5) a source of cooling water and (6) suitable hose and cable for connecting this equipment. Additional equipment such as a motor-driven carriage and welding fixtures are usually used for machine welding.

Torch or Electrode Holder

The torch or electrode holder is one of the most important items of apparatus for inert-gas metal-arc welding. Its good performance is fundamental in the successful application of the process. The sketch in Fig. 1 shows a sectional drawing of a holder with the essential working parts identified. The functions and requirements of each part of a holder will be described starting from the arc and progressing back to the welding machine. The arc is an intense source of heat for welding. Most of the heat of the arc is absorbed by the base metal but a portion of the heat of the arc goes into the electrode. The electrode material should be practically non-consuming and only two materials have been found to be usable. Tungsten electrodes are most generally used but carbon electrodes have found a limited use for low-current welding. The temperature of the end of the electrode is very high, being near the melting point of tungsten. The temperature differential between the end and the point of support of the electrode results in a considerable flow of heat into the holder. A portion of the heat in the electrode is radiated and some of this radiated heat is absorbed by the gas nozzle which surrounds the hot electrode.

The electrodes are held in place by clamps or some other easily adjusted gripping devices. Another requirement of the electrode clamps is that they be interchangeable to accommodate a range of sizes of electrodes for the range of welding current for which the holder is designed. The clamps conduct the welding current from the holder to the electrode and also conduct heat from the electrode to the holder.

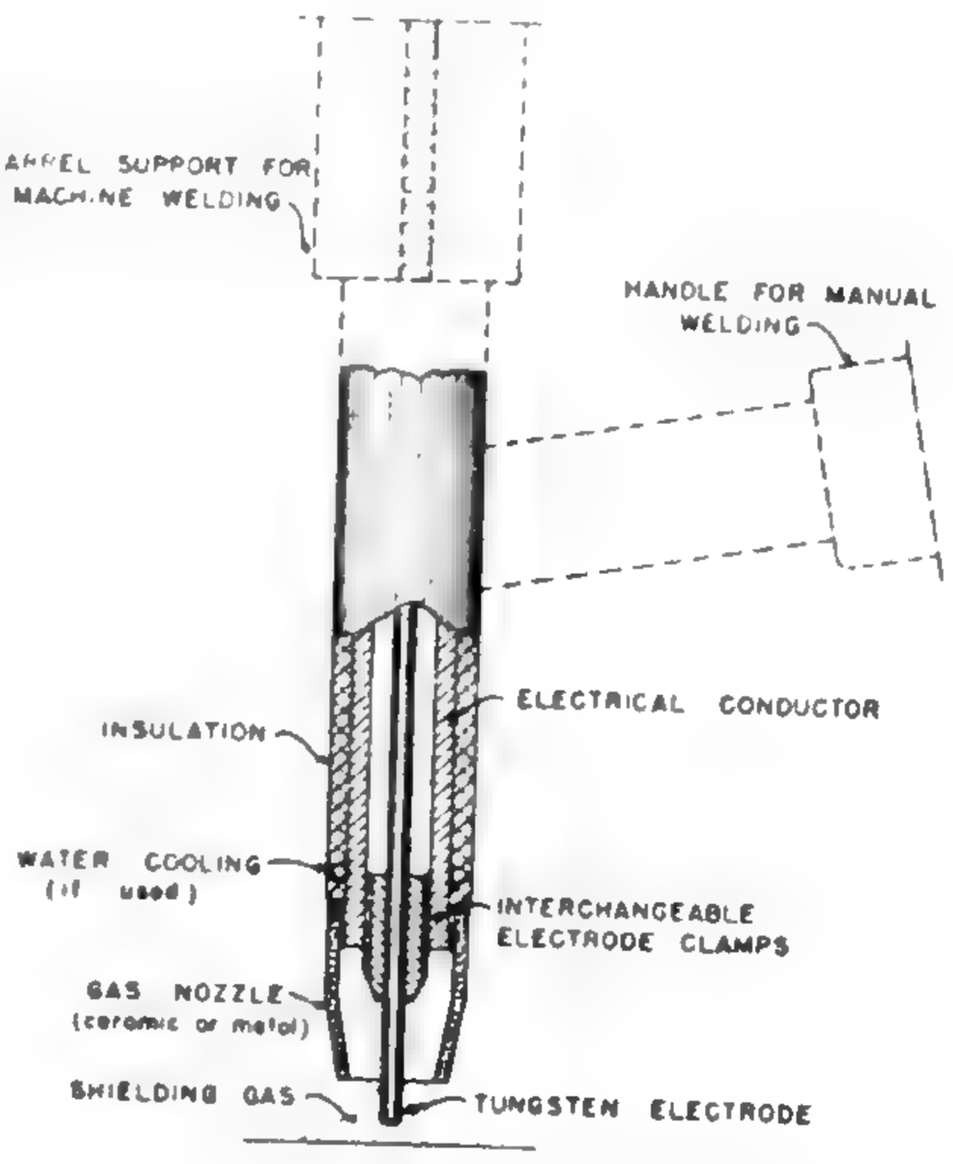

Fig. 1.—Typical Electrode Holder for Inert-Gas Metal-Arc Welding

The principal function of the gas nozzle is to direct the flow of shielding gas around the electrode, arc and weld puddle, thus shielding them from the air. To accomplish this, the geometry of the gas nozzle must be such as to produce a uniform gas flow at the orifice of the nozzle. The material of the nozzle must be highly heat resistant or capable of con-

ducting the heat away from the lower edge so that it does not overheat by radiation from the electrode. Gas nozzles are usually made of refractory ceramic compositions or of metal. Metal nozzles for high welding currents are usually water-cooled.

A further requirement of gas nozzles is that they be electrically insulated from the electrode potential or be made of a non-conducting material. This is necessary to prevent arcing from the gas nozzle to the work. The use of metal nozzles requires sufficient clearance between the nozzle and electrode to prevent injuring the nozzle by arcing. The service conditions for gas nozzles are so severe that they should be readily replaceable. It is also usually desirable to have nozzles of two or three sizes for the same holder to suit the welding current and other job requirements. Larger electrodes are required to carry the higher welding current used for welding thick material, hence larger gas nozzles are used.

The body of the holder supports the electrode and should hold the gas nozzle concentric with the electrode. The holder must also conduct the welding current and gas from the flexible leads to the electrode clamp and gas nozzle, respectively. When water cooling is used the water should be circulated to a point as close as practical to where the electrode is gripped. The water flow may also be used to cool the current conductor in the holder so that lightweight construction may be used. This is particularly important in the manual type holder. When no water cooling is used, the current capacity and duty cycle are determined by overheating of parts of the holder. The temperature of the handle should never become high enough to produce discomfort when a welder holds the handle in his gloved hand. The shape of the body of the holder is determined by its intended use. A manual holder should be of the lightest permissible construction and have a handle positioned at an angle of 90 deg. or greater with the axis of the electrode. The location of the handle relative to the arc should be determined by the current capacity of the holder and by its ability to be used in restricted areas. A straight barrel type holder is generally more suited for machine welding. A straight holder may be mounted on a travel carriage using the same positioning fixture as used with oxygen-cutting equipment.

The electrode holder must be supplied with electric current and shielding gas. Water-cooled holders must have a supply of cooling water. This is conducted to the holder by means of flexible tubes and copper cable. When the holder is of the manual type it is usually desirable to cool the conductor cable by enclosing it in one of the water supply tubes or hose, which permits a very light flexible conductor. The insulation of the cable must have sufficient dielectric strength to help prevent excessive leakage of high-frequency stabilizing voltage when it is used. Finally, it is necessary to protect the electrode leads from abrasion, hot objects and other service conditions. It is convenient and desirable to enclose or tie all leads together for about 10 ft. from manual-type holders.

Shielding Gas

Either argon or helium is used as the shielded gas for practically all applications of this process. These two gases are monatomic and welding arcs in an atmosphere of either argon or helium are remarkably smooth and quiet.

Both the argon and helium used must be of high purity. The presence of small amounts of moisture, hydrogen or hydrocarbons will result in porous welds. As a result, the argon or helium used as the shielding gas should be of 99.8% minimum purity. Many other gases and gas mixtures have been tried, but they all have some deficiencies causing rapid erosion of the electrode, porosity in the weld metal or arc instability.

The basic characteristics of argon and helium may be briefly summarized as follows:

Argon provides a better cleaning action for aluminum and magnesium when welding with alternating current. Under similar welding conditions, less argon than helium is required and with alternating current argon provides a more stable arc.

Helium, for a given current, provides a higher arc voltage and a higher welding heat.

Control Equipment

The selection of control equipment for inert-gas metal-arc welding is largely a question of economics. One important purpose of control equipment is to save gas; another purpose of control equipment is to save welding time. In simple ap-

plications where the use of the holder is infrequent, only the most essential control equipment is justified. On the other hand where the process is used continuously in production involving elaborate jigs and the fabrication of high cost materials it is economical to provide the necessary control equipment.

Gas-control equipment should provide a uniform flow of the desired quantity of gas during the time it is needed. Gas is usually supplied in high pressure cylinders or by a piped system supplied from a cylinder manifold. In either case a pressure regulator is necessary to provide for a uniform flow. A graduated glass tube flowmeter is used to indicate the rate of flow. These flowmeters are supplied either separately, so they can be installed anywhere in the line, or incorporated with the regulator. A flow of gas is needed for a short period of time before the arc is struck in order to purge the gas lines and holder of air. The gas flow is necessary, of course, during welding and it is also necessary for the gas to flow after the arc is broken until the tungsten electrode has cooled down to black heat to protect the electrode from oxidizing in the air.

In most welding operations the arc is maintained for only short periods and there are many starts and stops during a day's operation. In order to avoid wasting gas it should be very convenient for the welder to turn the gas off and on at the proper time. An electric solenoid gas valve or quick-acting, mechanical valve may be installed in the gas line which can be controlled at or near the point of welding. The gas valve control can be tied in with arc control apparatus so that its operation is automatic.

Control of welding current can be divided into three different categories. Probably the most commonly used control operation is to break the welding current at the end of the seam. In manual welding it is a simple matter to break the arc but in machine welding it is usually desirable to break the current at some other point in the welding circuit than the arc. Breaking the welding current may be done in many ways, but a common method is to have a contactor in the circuit. It is sometimes necessary and desirable to decrease the welding current rapidly but not instantaneously at the end of a weld so that weld craters may be filled up or be eliminated. One method of accomplishing this with motor-generator welding machines is to shut off the power supply and let the inertia of the machine fade off the welding current. Another type of welding current control is the use of remote current control to adjust the welding current throughout the welding cycle. Foot control is often employed. Current adjustment of this nature is quite useful.

It is often desirable to start the arc without touching the electrode to the work-piece, principally to avoid contamination of the electrode. This is usually accomplished by a high-frequency spark across the arc gap. High-frequency starting is very convenient for remote control starting for machine welding and it can be used with both alternating and direct current.

Most electrode holders are water-cooled and the continued flow of the proper volume of water is vital in the protection of the holder and water-cooled current cables. If the water supply should fail, a method of control should be provided to stop the welding operation. One method is to use a water-cooled, fusible link in the welding current lead. Another is to provide a water interlock in the electrical control circuit which is actuated by a pressure switch on the discharge water, or by a water-flow switch.

A final step in control of inert-gas metal-arc welding is automatic control of arc length. This involves an automatic welding head which is an elaborate piece of equipment as compared with the control equipment previously discussed. An automatic welding head raises and lowers the electrode holder to maintain a constant arc length as it traverses a work-piece of uneven contour. Usually only production jobs of large quantities justify the use of an automatic head. Another method is to use a shape-tracing machine which follows a template. The mounted torch will weld a complicated curved section of the same shape as the template.

Unbalanced vs. Balanced Wave Alternating Current Machines

For welding aluminum, magnesium and beryllium copper two general types of welding circuits are employed, both using alternating current. One is an a.c. transformer having superimposed high frequency in the welding circuit for arc stabilization. These transformers have

open-circuit voltages of about 60 to 100 volts which is sufficient to maintain stable arc conditions. As the welding current goes through the zero point of the usual a.c. wave, there is the possibility of partial, incipient or complete rectification of the reverse-polarity cycle. This loss of part of the welding cycle results in loss of cleaning action, uneven heating and uneven weld appearance. A high-voltage, high-frequency current of low amperage is therefore superimposed on the usual 60-cycle alternating welding current in order to stabilize the arc.

However, one other disadvantage results from the use of the usual arc-welding transformer in conjunction with this process, namely that the welding current becomes unbalanced. There is always a d.c. component, that is the straight-polarity half of the a.c. cycle is of greater amplitude and duration than the reverse-polarity half of the a.c. cycle. This necessitates substantial derating of the usual transformer.

With an unbalanced wave transformer a higher welding current can be carried by a given size electrode, but the disadvantages are that the transformer core becomes saturated due to the d.c. component with the resulting higher primary current flow. The transformer must therefore be derated to about 70% for inert-gas metal-arc welding as compared to shielded metal-arc welding.

The other type of transformer welding machine now being used employs series capacitors giving a balanced wave type; that is the reverse polarity and straight polarity half cycles are approximately of equal amperage and duration. Weld penetration for a given amperage is also somewhat higher than that possible with the unbalanced wave. (See Chapter 8 for further information on welding machines and other equipment.)

Auxiliary Equipment

Mechanized or semi-automatic applications of inert-gas metal-arc welding usually require a travel carriage on which to mount the holder in order to traverse the work at uniform speeds. The travel carriage should be provided with a mounting bracket for the holder so that it may be easily and quickly adjusted vertically and normal to the direction of travel. The carriage should have a steady rate of travel adjustable over a range of speeds for which the process is suited. A speed range of from 6 to 60 in. per min. will include the majority of the applications although welding speeds up to 150 in. per min. have been reached. The carriage and track must be stable in order to maintain the arc length within close tolerances. Equipment used for machine oxygen cutting will usually be found suitable for machine inert-gas metal-arc welding.

Mechanical feeding of welding rod is quite often necessary for mechanized inert-gas metal-arc welding. Fillet welds in all materials require the addition of filler metal. Butt joints in material thicker than $^1/_{16}$ in. usually require the addition of filler metal to maintain full section welds. Filler metal can often be preplaced in the joint before welding but this usually complicates the fit-up and is seldom practical. Filler metal is fed to the arc ahead of the electrode, and is melted without touching the electrode. The molten metal runs under the electrode and flows up behind the arc to form the fillet or the weld reinforcement. In most cases the filler metal can be fed to the arc at a steady rate and the resulting welds are uniform in section and in appearance when the proper welding procedure is used.

The inert-gas metal-arc welding process has found a wide field of application in material thicknesses of $^1/_8$ in. and less. The most important factor in welding thin material is having accurate jigs and fixtures for holding and positioning the work. Jigs can be constructed so that they will move under a fixed position holder or so that the torch moves over the jig. One main function of jigs and fixtures is to hold the edges to be joined together and in alignment while welding. Another common function is to provide support and protection to the under side of the weld bead. In the design of jigs cognizance must be taken of the heat flow problem from the standpoint of maintaining a constant temperature of the jig itself and not draining the welding heat from the joint too rapidly. Thin material must be supported close to the edge of the joint and the heat drain problem is difficult when the material has high heat conductivity. Each weldment usually requires a special jig and the design and construction of the jig must be determined by the user.

CONSUMABLE ELECTRODE METHOD

A new method of inert-gas metal-arc welding has recently been introduced. This method is distinctly different than the method previously described in this chapter in that the electrode is consumed and transfers to the weld puddle where it becomes part of the joint. The electrode consists of a continuous bare wire, usually similar in composition to the base material, and is fed into the arc at the rate at which it is consumed. Direct current is used and other characteristics are similar to the characteristics of the methods using tungsten or carbon electrodes. However, the deposition rates are higher for this method than for the methods using non-consuming electrodes

This method is relatively new and further development is now in progress. Both manual and machine equipment are available. With manual equipment, welds can be made in all positions.

In machine welding a conventional type automatic welding mechanism is used to feed the electrode to the arc, the rate of feed being controlled by the arc voltage

Manual equipment includes a welding gun which is connected by means of flexible hose to a wire feeder and the operation of the gun is continuous for long lengths of weld. Electrodes are available in coils in sizes ranging from $^{1}/_{32}$ to $^{3}/_{32}$-in. diam and they are flexible enough to allow free manipulation of the gun. Very high current densities are used in the electrodes, for example 400 amp. for $^{3}/_{32}$-in. diameter. This use of high current densities results in a smooth arc and a spray-type metal transfer with very little spatter.

This method of inert-gas metal-arc welding has been developed for welding aluminum and stainless steel, but preliminary studies indicate that it will be suitable for all metals and alloys commonly arc welded. These include magnesium, copper, aluminum bronze, nickel and Monel as well as plain carbon and low-alloy steels. There appear to be particular advantages for this method in making small, well-shaped fillet welds at high speed, even on heavy material. Further information on this method of inert-gas metal-arc welding will be found in some of the articles listed in the bibliography at the end of this chapter and future developments will no doubt be reported in *The Welding Journal* and other technical publications as they occur.

COMMON APPLICATIONS

Aluminum and magnesium are now being welded with inert-gas metal-arc welding because of high weld quality and low overall cost. Figure 2 shows the welding of an aluminum pressure vessel in which the welding is done from both sides. Since no flux is required, no flux can be entrapped in the weld and therefore the corrosion resistance of the weld is improved. Flux cleaning is eliminated and sound welds of good tensile strength and ductility are produced. The ease of welding with this process has also played a large part in its increased use.

Fig. 2.—Inert-Gas Metal-Arc Welding Aluminum Pressure Vessel

The process is being used for welding sheet steel. A high manual welding speed is possible with resulting low distortion of the welded assembly. No flux is required and therefore flux cleaning is eliminated. The amount of weld reinforcement can be controlled closely because the welding rod is added separately and therefore the grinding costs are much lower where the reinforcement must be removed. This is particularly true in the case of butt welding automobile fenders and bodies. Figure 3 shows an automobile fender which has been fabricated by inert-gas metal-arc welding two drawn parts. In many cases the grinding costs are

Fig. 3.—Automobile Fender Fabricated by Inert-Gas Metal-Arc Welding

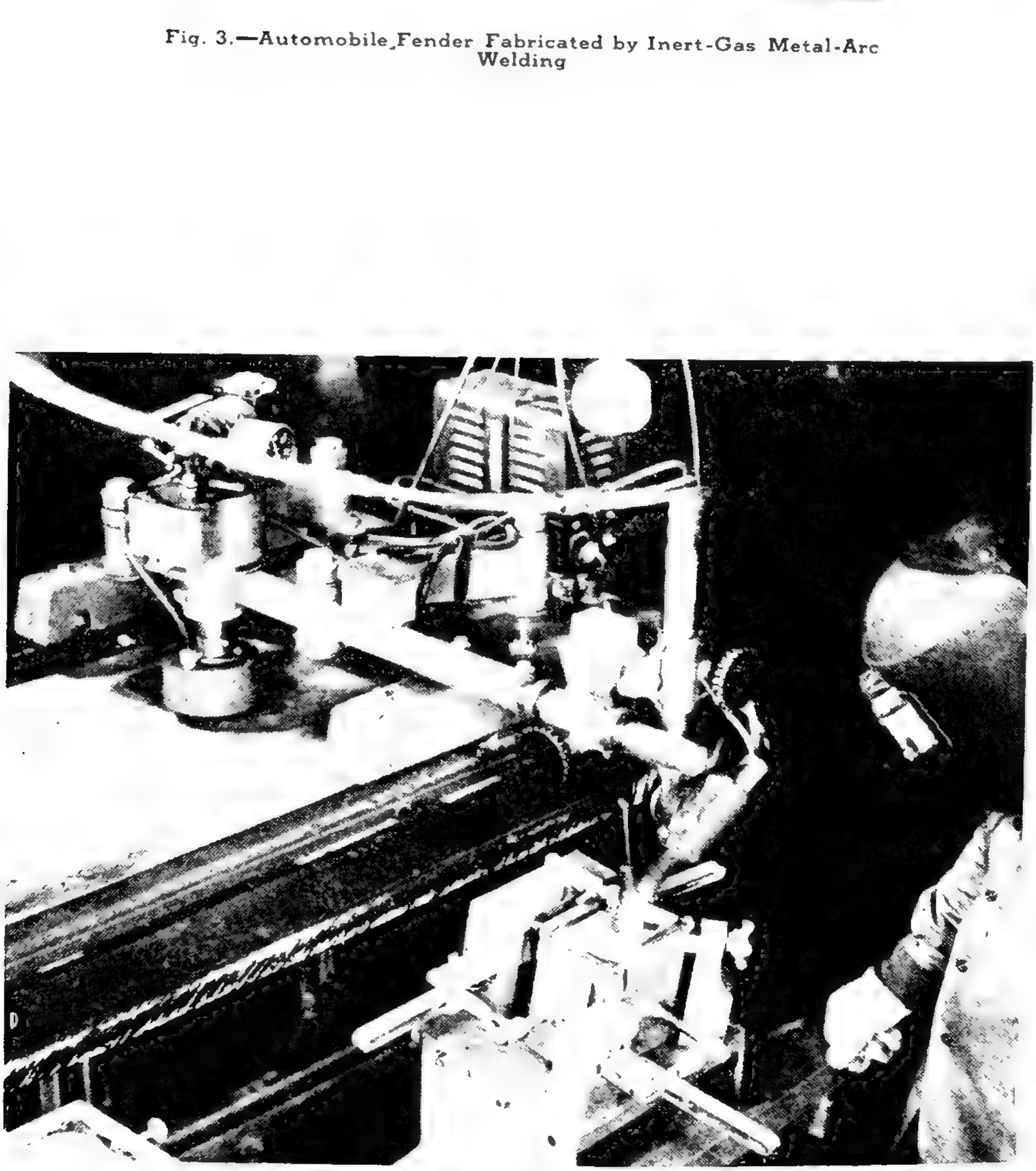

Fig. 4.—Stainless Steel Box Welded by Template-Guided Electrode Holder

many times greater than the welding cost so that the resulting reduction in grinding cost has lowered the overall joining cost by a considerable amount. The same reasons apply to welding of thin sections of practically all other metals, such as stainless steel, low-alloy steel, copper, high-temperature alloys, etc.

Another important reason for use of this process for welding stainless steel of all thicknesses is the saving in the cost of filler metal; over 90% of the welding rod is deposited as weld metal. Also less time is required for wire brushing and chipping between weld passes in multiple-pass welding of heavy material. Figure 4 shows the welding of a stainless steel box by use of an electrode holder which is mounted on a template-guided carriage.

The welding of deoxidized copper has increased because sound welds can be made at a high rate of welding with a copper welding rod so that the resulting welds have good corrosion resistance, tensile strength and ductility. Peening is not required with the use of a string bead technique. No flux is required and therefore no flux can become entrapped in the weld metal so that the resulting corrosion resistance is good. For further information on the welding of a particular metal refer to the chapter on that metal.

The process is now being used for surfacing because the resulting dilution of the surfacing alloy with the base metal is low and there is little porosity.

Many dissimilar metals are being joined. Because the weld puddle can be seen so clearly, and because the welding rod is added separately, very good control of filler metal addition is possible. This is important in welding most dissimilar metals. Excessive dilution of the dissimilar metals is usually to be avoided. A fast rate of welding with little resulting distortion is possible.

BIBLIOGRAPHY

1. *Heliarc Welding of Stainless Steel*, T. E. Piper, The Welding Journal Res. Suppl., October 1942
2. *Helium-Shielded Arc Welding of Magnesium Alloys*, F. A. Wassell, The Welding Journal, February 1944.
3. *Characteristics of Welding Arcs on Aluminum in Atmospheres of Helium and Argon*, F. A. Wassell, The Welding Journal Res. Suppl., May 1944.
4. The *Heliarc Welding Process as Applied in the Aircraft Industry*, T. E. Piper, The Welding Journal, October 1945.
5. *Gas-Shielded Arc Welding of Aluminum*, A. F. Leach, The Welding Journal, December 1945.
6. *Production Applications of Inert-Gas Shielded-Arc Welding*, H. T. Herbst, The Welding Journal, May 1947.
7. *Inert-Gas Shielded-Arc Welding Process*, G. J. Gibson, The Welding Journal Res. Suppl., May 1947.
8. *Inert-Arc Welding Currents for Use with Tungsten Electrodes*, R. W. Tuthill, The Welding Journal, September 1947.
9. *Heliarc Welding for the Difficult-to-weld Metals*, H. T. Herbst and F. J. Pilia, Product Engineering, January 1948.
10. *Mechanized Inert-Gas Shielded-Arc Welding*, H. T. Herbst, The Welding Journal, February 1948.
11. *Power Supply for Inert-Arc Welding*, A. V. Welch, The Welding Journal, May 1948.
12. *Construction and Maintenance of Railroad Equipment by Submerged and Gas-Shielded Electric Welding*, N. G. Schriener and J. M. Tippett, The Welding Journal, June 1948.
13. *Electrical Characteristics of the Arc in Heliarc Welding*, H. T. Herbst, The Welding Journal, August 1948.
14. *Inert-Gas Shielded-Arc Welding Pure Copper*, J. W. Mortimer, The Welding Journal, September 1948.
15. *The Effect of Wave Shape in Inert-Arc Welding Circuits*, R. W. Tuthill, The Welding Journal, October 1948.
16. *The Effect of D.-C. Component in A.-C. Inert-Gas Arc Welding of Aluminum*, G. J. Gibson and G. R. Rothchild, The Welding Journal Res. Suppl., October 1948.
17. *The Gas-Shielded Metal-Arc Welding Process*, J. Sohn and A. N. Kugler, The Welding Journal, November 1948.
18. *Hard Facing with Inert-Gas Arc Welding*, K. H. Koopman, The Welding Journal, January 1949.
19. *Inert-Gas Shielded-Arc Spot Welding*, F. J. Pilia, The Welding Journal, January 1949.
20. *Heliarc Welding Light Metals*, Modern Metals, March 1949.

CHAPTER 13

SUBMERGED ARC WELDING*

FUNDAMENTALS OF PROCESS

Definition and General Description

SUBMERGED ARC welding is an arc-welding process wherein coalescence is produced by heating with an electric arc or arcs between a bare metal electrode† or electrodes and the work. The welding is shielded by a blanket of granular, fusible material on the work. Pressure is not used and filler metal is obtained from the electrode and sometimes from a supplementary welding rod.

[NOTE: The granular, fusible material mentioned above has been variously called welding composition, melt, flux, etc. While this material is not properly designated as a flux because it performs more than the functions usually ascribed to a flux, the term *flux* will be used in this chapter for purposes of simplicity.]

Principles of Operation

The welding operation may be started by any one of several methods. Most often it is started by striking an arc beneath the flux on the work. It may also be started by creating an ionized path by use of a high-voltage, high-frequency current or by initially interposing a piece of steel wool, carbon or other high-resistance conductor between the electrode and the work. The heat produced by any of these methods melts the immediately surrounding flux so that it forms a subsurface conductive pool which is kept fluid by the continued flow of welding current. The end of the metal electrode and the work-piece directly under it become molten and molten filler metal is deposited from the metal electrode onto the work. The molten filler metal displaces the fluid flux and forms the weld, the shape and volume of which depend upon the speed of electrode travel and other conditions. As welding progresses, both the molten filler metal and the molten flux forming a fluid protective blanket above the filler metal, cool and solidify under the unfused flux. There is some chemical reaction between the molten metal and the molten flux. Figure 1 shows how a single-vee groove weld is made. The fused flux floats to the top of the deposited metal and solidifies in the form of a brittle slag, which is readily removable.

Characteristics of Process and Effect on Materials Welded

Submerged arc welding is characterized by the use of high welding currents. The current carried in relation to the cross-sectional area of the electrode is often as much as six times as great as in manual shielded-metal-arc welding. Due to these factors the melting rate of the electrode is proportionally higher and the speed of welding greater.

In general the melting rate is affected by the type of electrode, flux, type of current (and polarity if d.c.) and extension of the electrode beyond the point where the current is introduced. A typical melting rate curve for mild steel electrodes is shown in Fig. 2.

Deep penetration can be obtained; consequently no groove or a small groove may be used, depending upon the thickness of the base metal, with correspondingly smaller additions of filler metal. No chamfering is necessary for two-pass butt joints in steel up to $^5/_8$ in. in thickness for many types of application and complete penetration can be obtained in

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* Prepared by a committee consisting of T. M. Jackson, Sun Shipbuilding & Drydock Co., *Chairman;* M. H. MacKusick, Welding Consultant; W. R. Persons, The Lincoln Electric Co.; N. G. Schreiner, The Linde Air Products Co.; H. N. Simms, Black, Sivalls & Bryson; H. S. Swan, American Locomotive Co.; R. F. Wyer, General Electric Co.

† Sometimes a lightly coated electrode is used.

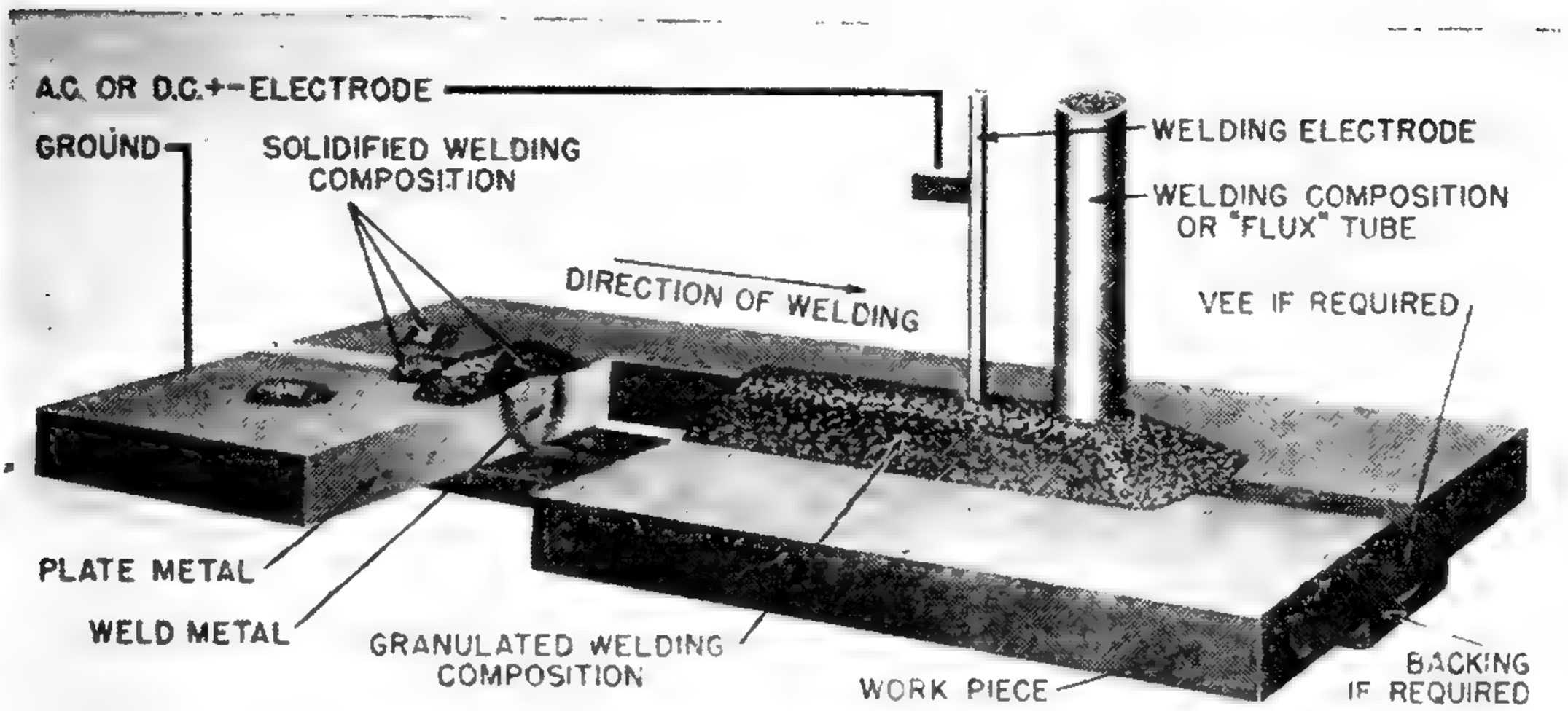


Fig. 1.—Single-Vee Groove Weld by Submerged Arc Welding

tee joints for material up to $^{3}/_{4}$-in. thick without chamfering. For joints in thicker material, a double-Vee groove weld is used, made with one pass from each side. Back chipping of the root is not necessary since, when welding on the second side, the penetration is great enough to extend into the weld made on the first side. Figure 3 shows typical relations between penetration and applied current.

The size of the groove and the amount of filler metal deposited by the higher current used to obtain deep penetration must be balanced if excessive reinforcement is to be avoided. Because of the deep penetration nearly two volumes of base metal are melted for each volume of filler metal melted. Hence the base metal so nearly determines the chemical and mechanical properties of the weld

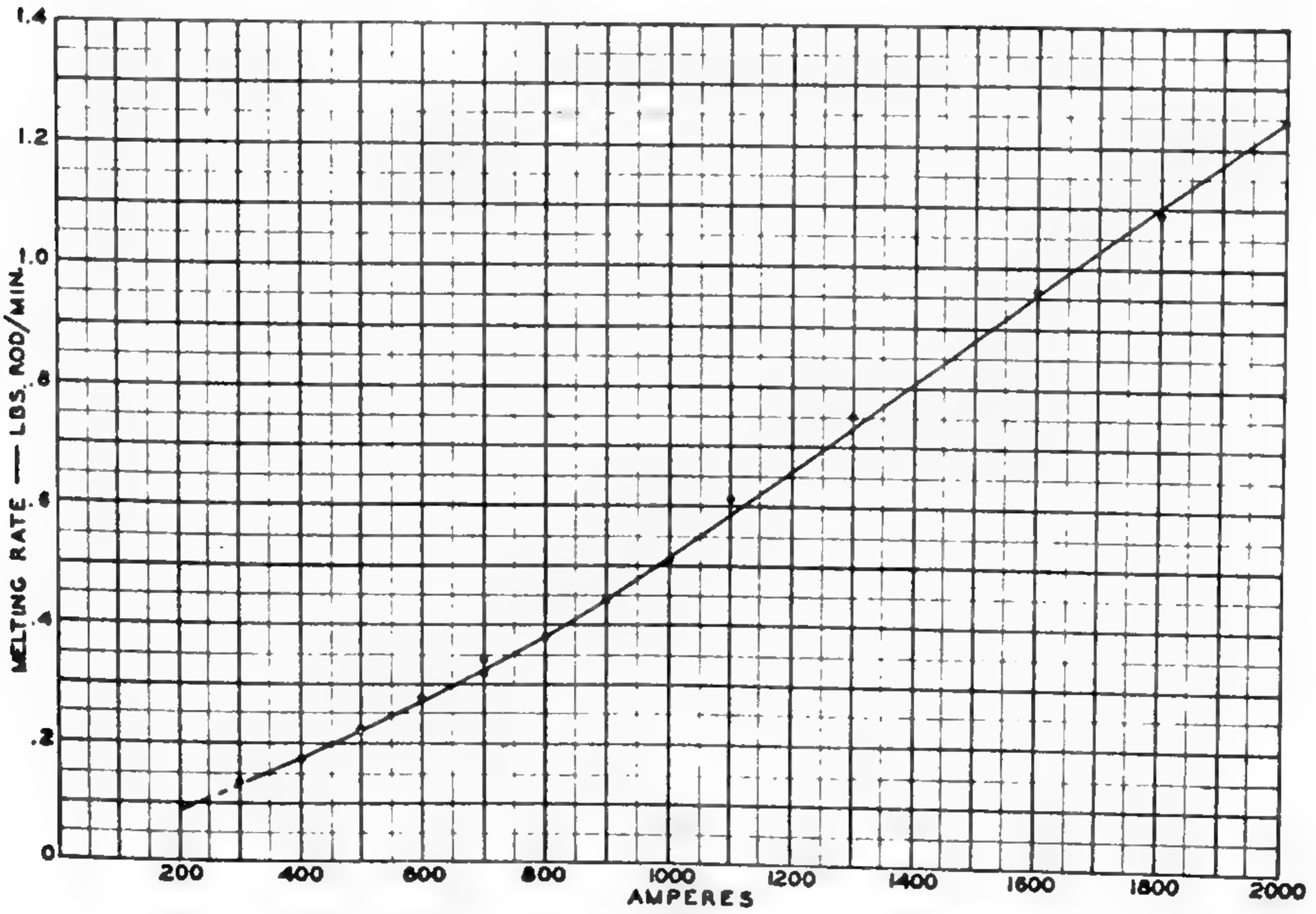


Fig. 2.—Typical Melting Rate Curve (Mild Steel Electrodes)

metal that for many of the low-alloy steels it is not necessary to use electrodes of the same composition as the base metal.

Cleaning of Welds.—Under usual welding conditions the quantity of flux which is melted weighs approximately the same as the electrode which is added. The unfused flux may be re-used after collection manually or by mechanical means such as by a suction unit similar to an industrial vacuum cleaner. Under certain conditions, the fused flux may be ground and re-used.

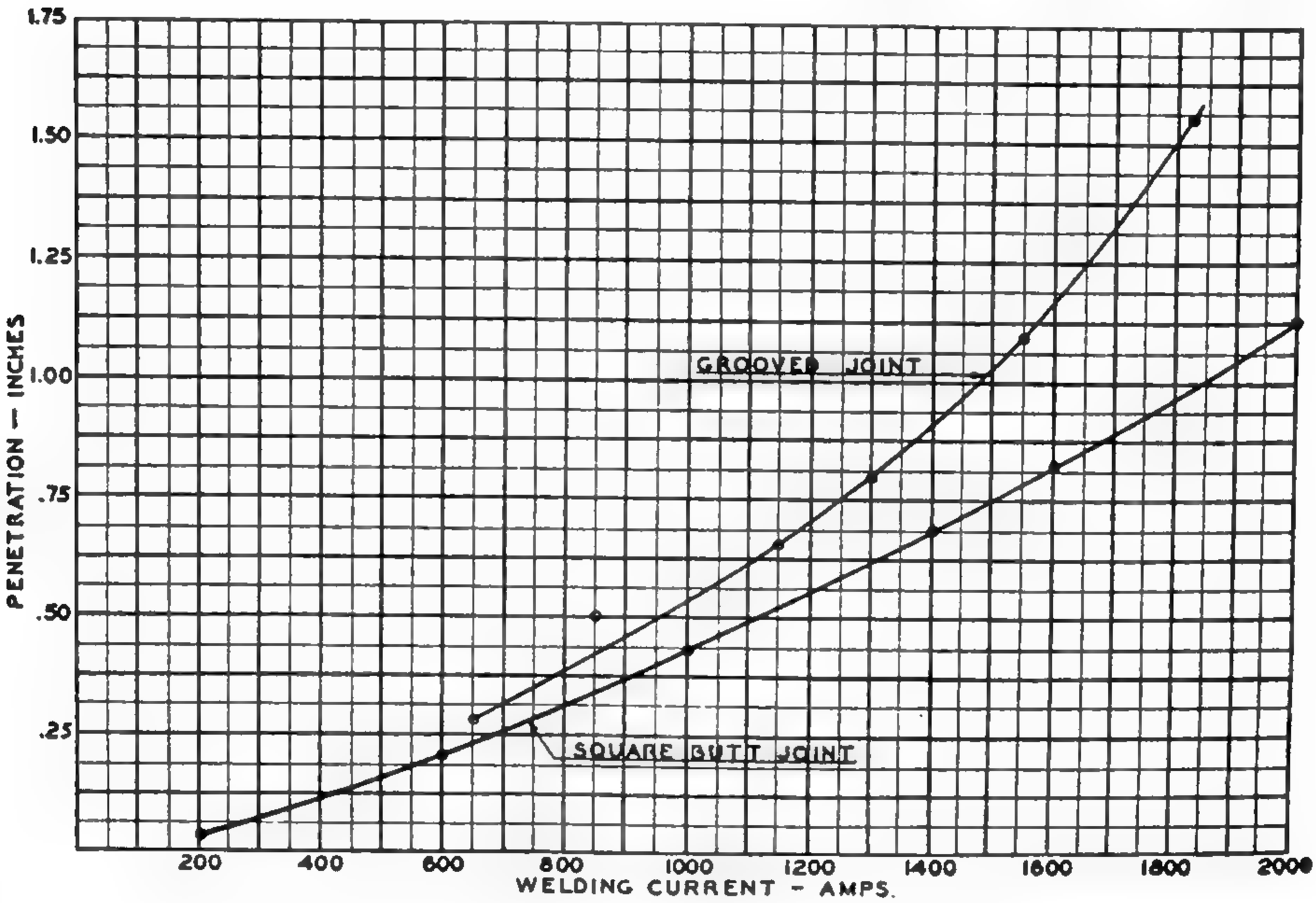


Fig. 3.—Penetration vs. Applied Current

Shrinkage.—The shrinkage in submerged arc welds is generally so small that it can be ignored. On long joints, however, it is measurable and average values are indicated in Table 1.

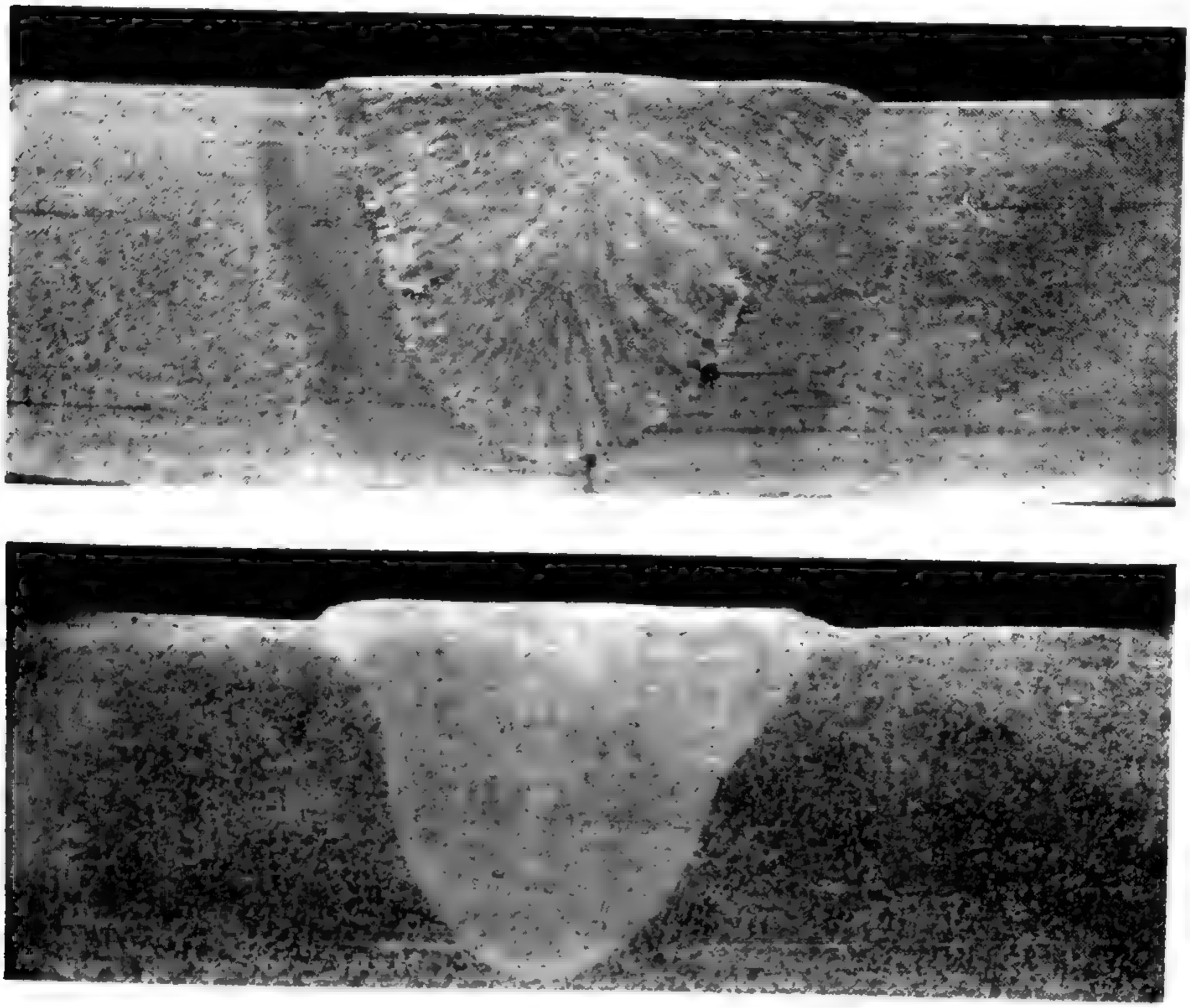
Transverse shrinkage of welds in butt joints will increase with an increase in root opening, with large groove-dimensions and with welding conditions which produce a wide weld. Longitudinal shrinkage of butt joints seems to be independent of these variables but is affected by plate thickness. Shrinkage in thin plates may be as much as 50% greater than the averages given in Table 1. Shrinkage of fillet welds in both directions is consistently close to the values given in Table 1.

Distortion.—With this process distortion of weldments is minimized because of the high welding speeds, minimum number of passes and efficient application of heat. Uniform application of heat and controlled welding conditions make distortion readily predictable so that it can be effectively offset.

Angular distortion of butt joint assemblies is generally small because of the balanced condition through the thickness of the joint. Distortion due to an unbalanced heat condition, as in single groove, multipass welded joints can be obviated by presetting the base metal parts to offset an angular movement determined by experience. Preset is dependent upon the thickness, width and shape of the members welded. For many cases, allowance for a 2-deg. angular movement is about right.

Angular distortion of the flange member of fillet-welded tee joints decreases the angle between flange and web by about 1 deg. 30 min. for $^1/_4$ to $^3/_4$-in. single-pass fillet welds. This distortion can be avoided by elastically prebending

(bowing) the flange member in the opposite direction to a greater angle (about $^{3}/_{4}$ in. deflection per ft.) or by plastically presetting the flange in a press 1 deg. 30 min. ($^{5}/_{16}$ in. per ft.); or it can be corrected by flame straightening after welding. Multiple-pass welding will increase this distortion, but not in proportion to the number of passes.



(Top) As-welded; (Bottom) After heating for 2 hr. at 1742° F. columnar structure almost completely removed.

Fig. 4.—Submerged Arc Weld in 2-In. Plate

Distortion in the longitudinal direction is relatively uniform since the weld is generally continuous from end to end of the joint. It manifests itself by a uniform bowing of the structure, which can be compensated for by elastic prebending as is practiced in the welding of center-sills for railroad cars or by balanced welding, as is possible in fabricating H-sections and box sections

Residual Stresses.—Investigations have disclosed that the residual stresses of submerged arc welds are no greater than those in ordinary arc welds joining similar weldments. Selected references appear in the bibliography at the end of this chapter, and further references may be found in Chapter 43.

Weld Quality

Submerged arc welds are generally strong, ductile, uniform in appearance, dense and have an unusually low nitrogen content. Mechanical properties of submerged arc welds are at least equal to, or better than, those of the base metal. Tables 2 through 7 give the mechanical properties of submerged arc welds in various ferrous and nonferrous materials.

Uniformly high quality welds require good quality homogeneous base material free from rust, scale, moisture and other surface impurities. Special techniques, which may require some sacrifice in weld-

ing speed and efficiency, must be used when welding less homogeneous material containing slag or other imperfections. Segregated sulfides in the base metal are particularly undesirable since heavy sulfide banding or segregation has been found to contribute to cracking along the dendritic boundaries as the weld metal cools. The length of such cracks can be minimized by multiple-pass welding.

Weld Structure.—The distinct dendritic structure revealed in macroetched cross-sections of single-pass welds made by the submerged arc process has sometimes been misinterpreted. Dendritic structure as encountered in castings, is generally considered undesirable, and it is quite natural that experienced investigators in some instances, have assumed that a similar structure in a weld is also unsatisfactory. However, test data and service experience have proved conclusively that such assumptions are unfounded and that, in the as-welded condition, the welds possess the desirable combination of strength and ductility. It has been shown that, in spite of its dendritic structure, the weld metal is more amenable to normalizing and recrystallization than the base metal, as can be seen in Fig. 4. Moreover, it has been definitely established that the shielding afforded by the flux against contamination by the atmosphere has much to do with the very good physical properties of the finished weld. In the as-welded condition, the fatigue strength, impact resistance, creep resistance and the normal and high-temperature tensile strength of the welds are generally equal to or superior to the corresponding properties of the base metal.

Welding Technique

Both butt and fillet welds can be made in the flat and horizontal positions, but so far the process has not been applied in the vertical and overhead positions. Welds made downhill have shallow reinforcement, sometimes hollow at the center, and may lack penetration, since the molten puddle has a tendency to flow ahead of the electrode and cushion the penetrating action. Permissible slopes at which welding can be done depend on the size of the molten pool of metal and amount of flux and may be as much as 20 degrees.

Circumferential or girth welds on rotating cylindrical assemblies are made by positioning the electrode ahead of the top center position so that the weld metal has a chance to solidify before the downhill slope becomes too great. This position is determined by experience. Figure 5 contains typical electrode positions for girth seams. The diameter of the assembly and the amount of fused flux that can be balanced are interdependent.

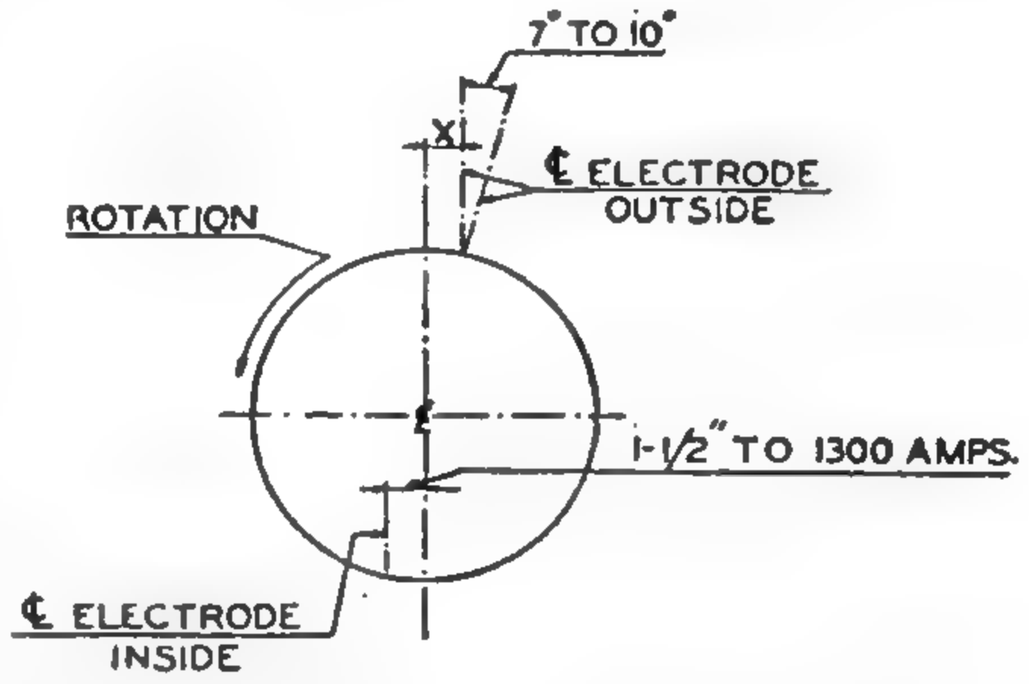


Fig. 5.—Electrode Positions for Girth Welds

Diam. of Drum, In.	*X*, In., (approx.)[a]
36 to 42	1 3/4
42 to 48	2
48 to 72	2 1/2
72 and up	2 1/2 to 3 1/2

[a] *X* should not vary more than 1/8 in. from a given setting for uniform results. If electrode is inclined as shown, *X* should be 1/4 in. greater. For inside welds add 1/4 in. for each 200 amp. above 1300.

Figure 6 shows the maximum usable currents for various girth diameters under normal welding conditions. The maximum usable current is affected by the welding speed and fluidity of the weld metal and flux.

Horizontal butt welds are made by preventing the free flow of the flux with suitable mechanical dams. Surface build-up with horizontal multiple-layer beads is made on vertical surfaces by this procedure.

Welding conditions generally require that a backing be used to prevent the molten metal from running out of the weld puddle. The usual backings are copper bars or water-cooled copper shoes or refractory material, e.g., flux. A large root face, a manual weld deposit, and a steel backing which becomes an integral part of the joint, are also used.

When a steel backing is used it should be continuous for the full length of the joint and not made up of short pieces butted end to end. Discontinuity in the length of an integral steel backing con-

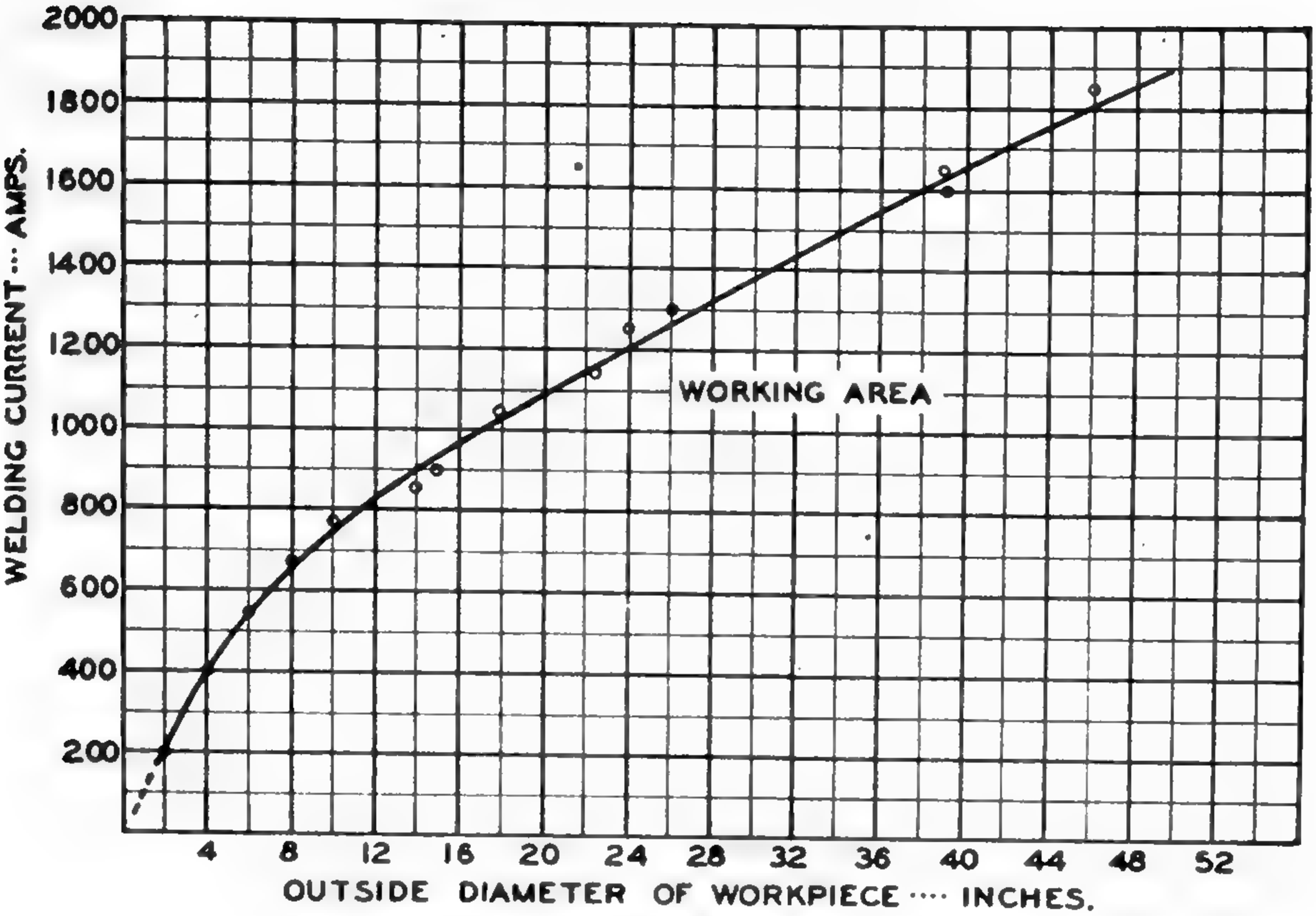


Fig. 6.—Maximum Welding Current for Girth Joints

stitutes a bad notch where longitudinal shrinkage may cause a transverse crack.

Cross-sections of the various forms of joint are shown in Figs. 7, 8 and 9. It will be noted that the illustrations show close fitting of the parts. This is highly desirable to assure sound welds and is essential if the molten metal is to be supported by the abutting faces of the joint.

Joint Design and Welding Conditions

Tables 8 through 18 give details of

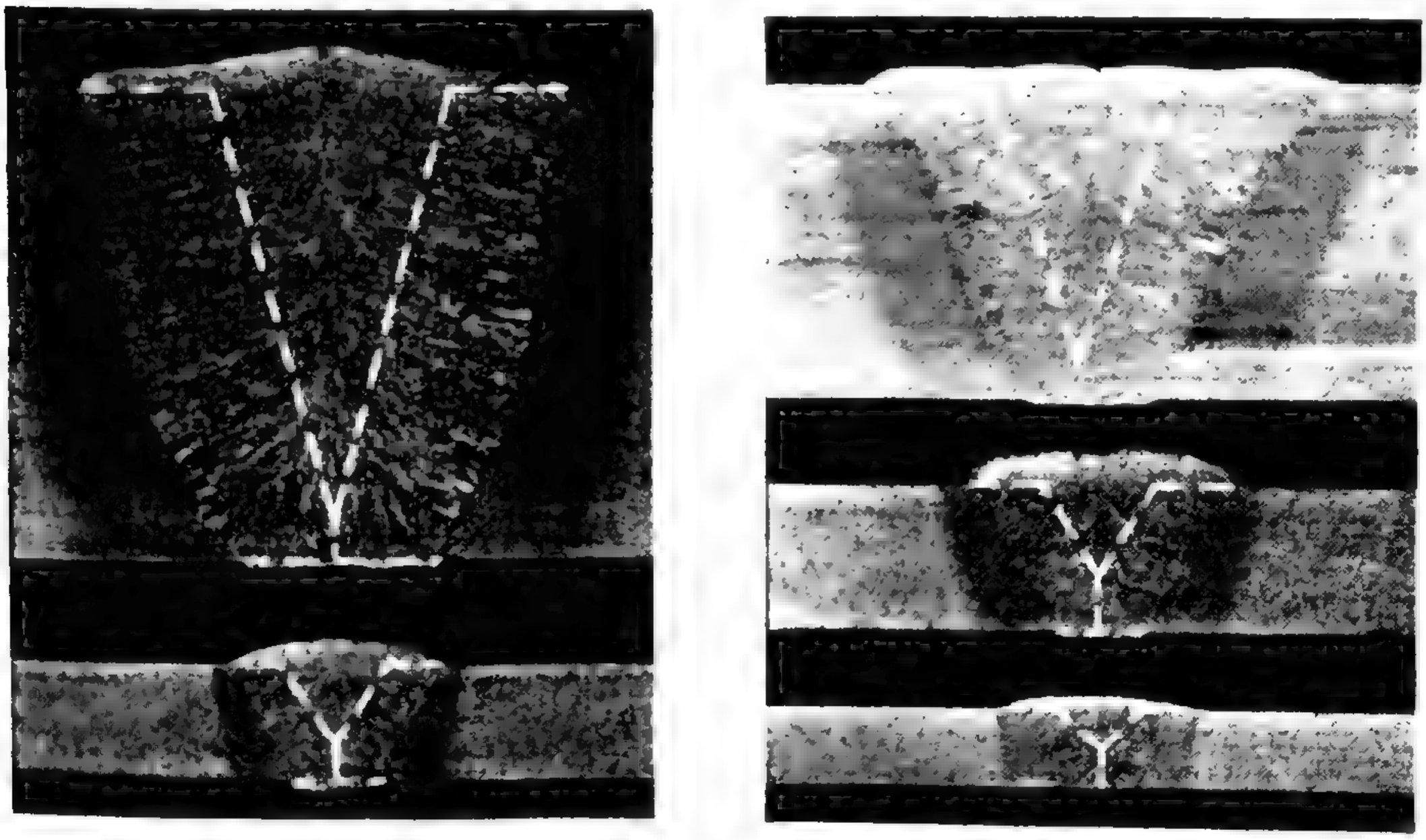


Fig. 7.—Single-Pass Groove Welds in 1/4, 3/8, 1/2, 1 and 1 1/2-In. Steel Plates with Suitable Backing to Insure Complete Penetration

typical joint design and welding conditions. The tables have been prepared as a composite of published data from various sources and the ranges of values are, therefore, broader than those usually shown. While suitable as a guide, this information should be modified to suit each particular application.

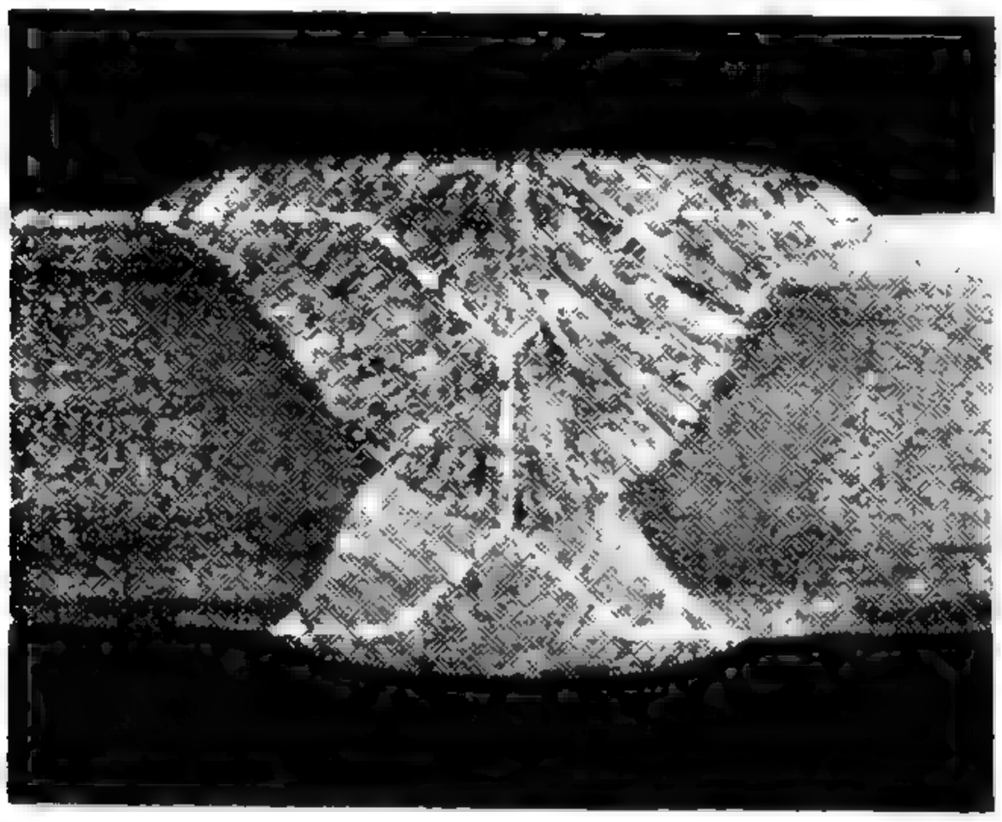


Fig. 8.—Butt Joint Made with Two Welds, One on Each Side

Used for plate 1/2-in. or more in thickness.

EQUIPMENT USED

Welding Heads

The specially designed welding heads most frequently used for this process perform the triple function of progressively depositing the flux along the joint, feeding the electrode, and transmitting welding current to the electrode. The flux is usually supplied from a hopper, either mounted directly on the head or connected to the head by tubing. The bare electrode is fed into the welding head in straight lengths or from a coil mounted on a reel. The distance between the end of the electrode and the base metal is maintained constant by a special automatic control which usually regulates the electrode feed by transmitting any slight variations in voltages across the welding zone into compensatory variations in the operations of the electrode-feed motor.

Electrical Equipment

Either a.c. or d.c. at from 20 to 55 volts across the welding zone can be used. Currents generally used are much higher than those used with other arc-welding processes and the largest available standard welding equipment can handle up to 4000 amperes.

Alternating current may be supplied from heavy-duty welding transformers (1000 amp. capacity or larger) with built-in motor-controlled reactors for adjustment of the welding current, and primary current contactors. These or smaller transformers of the same open circuit voltage may be paralleled when currents greater than those obtainable from a single transformer are required.

Direct current is generally supplied by standard single-operator motor-generator sets of a capacity suitable for the application. If the current required exceeds the output of a single generator (generally 300, 400 or 600 amp. capacity), two or more generators of the same type may be paralleled. Generating units of 1200 amp. capacity are available consisting of two 600-amp. generators closely coupled to each end of a single motor.

The intensity of the welding current of these d.c. machines is varied by means of field resistors or field taps. On certain applications constant-potential, d.c. generators may be used. In these installations variation in current is obtained by varying the series resistance. It is obvious

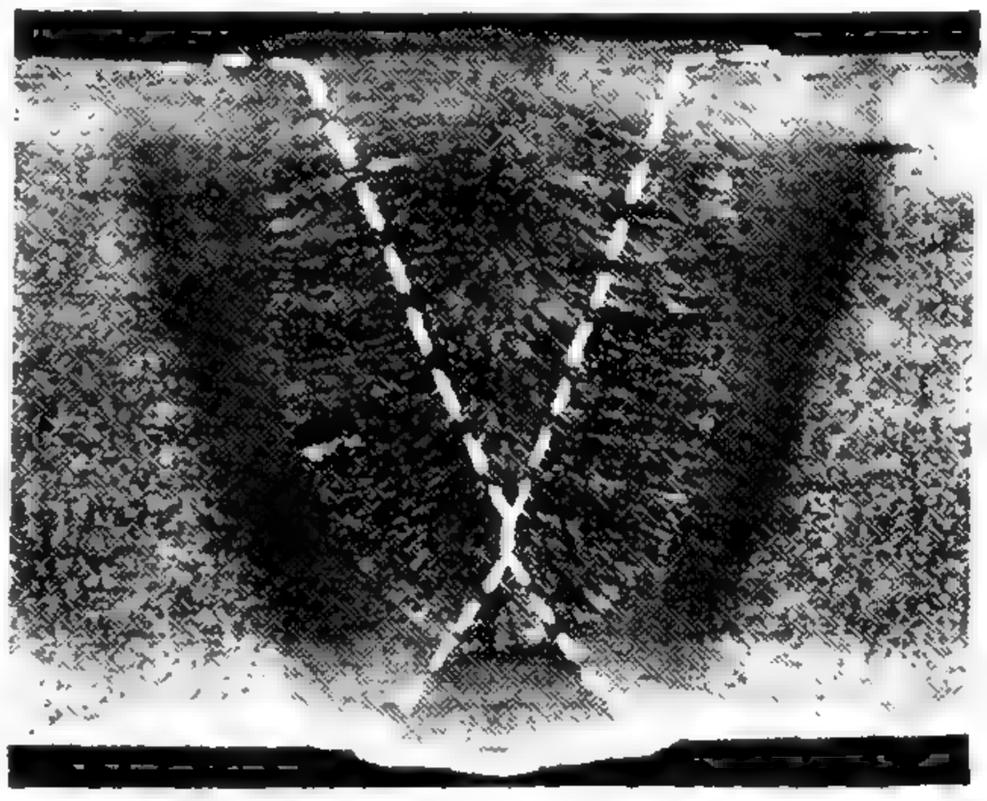


Fig. 9.—Double-Vee Groove Weld with Manual Backing Weld

that, because of the switching combinations necessary to effect a change in current, such an installation is desirable only in mass-production operations where the current need not be changed frequently.

The output from d.c. generators is controlled either by a large contactor in the welding circuit or by a small contactor

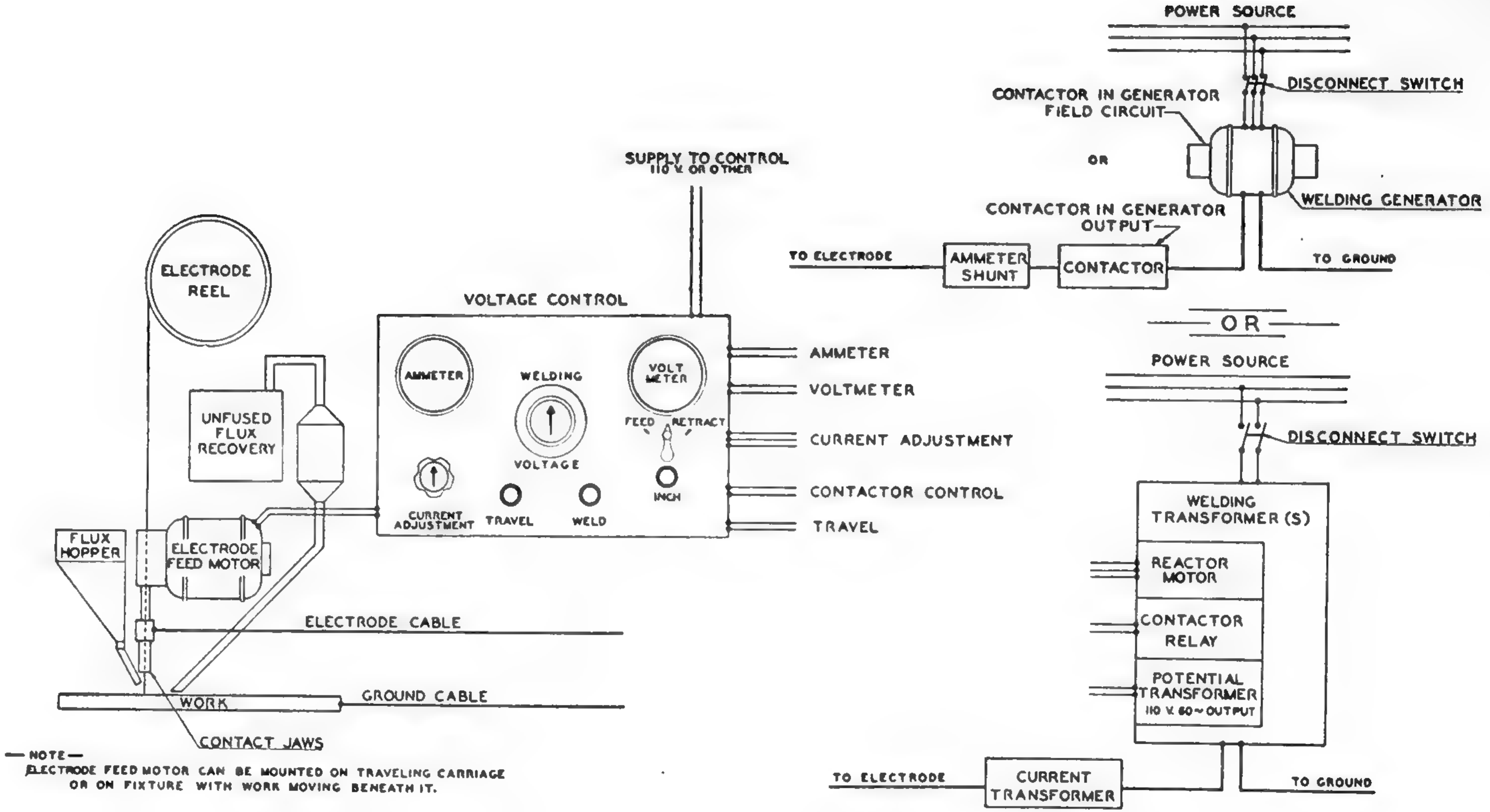


Fig. 10.—Schematic Drawing of Typical Automatic Submerged Arc Welding Equipment

in the generator field circuit, depending upon the construction of the generator.

Equipment Installations

Figure 10 indicates schematically typical equipment required for a fully automatic submerged arc-welding installation. Figure 11 shows one form of manually operated equipment. With this equipment, the welding operator simply allows the electrode, which projects from the contact jaw, to melt off at a rate controlled by the current, at the same time maintaining the desired voltage by elevating or depressing the tip of the rod.

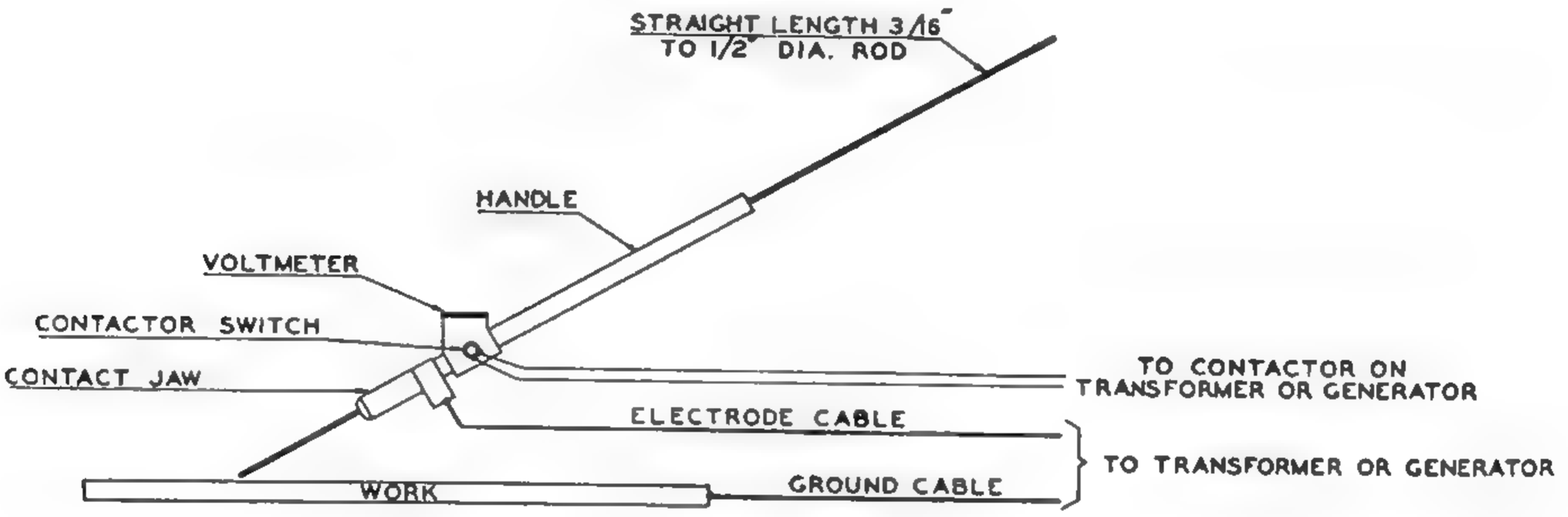


Fig. 11.—Schematic Drawing of Typical Manual Submerged Arc Welding Equipment

Figure 12 indicates another type of manually controlled semi-automatic equipment. Here only the direction of the weld is controlled by the operator; electrode feed, melting rate and voltage are automatically controlled. A high degree of maneuverability is possible with this equipment not only due to its design but also because of the small diameter of electrode used, current densities being somewhat higher than with fully automatic equipment.

The welding head may be mounted on a movable carriage, which may be portable, and thus moved in relation to the work; or it may be mounted on a stationary support with the work moving beneath it. For mass production operations, the welding head is usually built into the work-handling and jigging equipment. Details of various methods of application will be found in articles listed in the bibliography at the end of this chapter.

Vacuum units for the recovery of unfused granulated materials for re-use may be electric motor or air operated.

Electrodes

The electrodes commonly used with this process are bare rods or wires with clean bright surfaces to facilitate the introduction of the relatively high currents. Electrodes are normally used in the form of coils, although sometimes straight lengths up to 16 ft. long are used. Steel wire of composition that might readily rust is originally lightly copper-coated to retard rusting and improve the contact surfaces.

Rod is used for electrodes in the following compositions depending on the material being welded and the flux used:

(*a*) Low-carbon steel—for welds in 55,000 to 65,000 psi. tensile steels, and in high-tensile steels if stress relief is not required.

(*b*) Low-carbon alloy steel—for welds in 70,000 psi. and other high-tensile steels.

(*c*) Special alloy steels to meet chemical composition requirements of SAE constructional steels.

(*d*) High-carbon and high-carbon alloy steels for surfacing.

(*e*) Stainless steel and nonferrous alloys of composition to match the base metal.

Fluxes

The fluxes used with submerged arc welding are granulated, fusible mineral materials which are substantially free from substances capable of evolving large amounts of gases during welding. Although silica is an ingredient, there is no free silica in the finished product and no health hazard in its normal use.

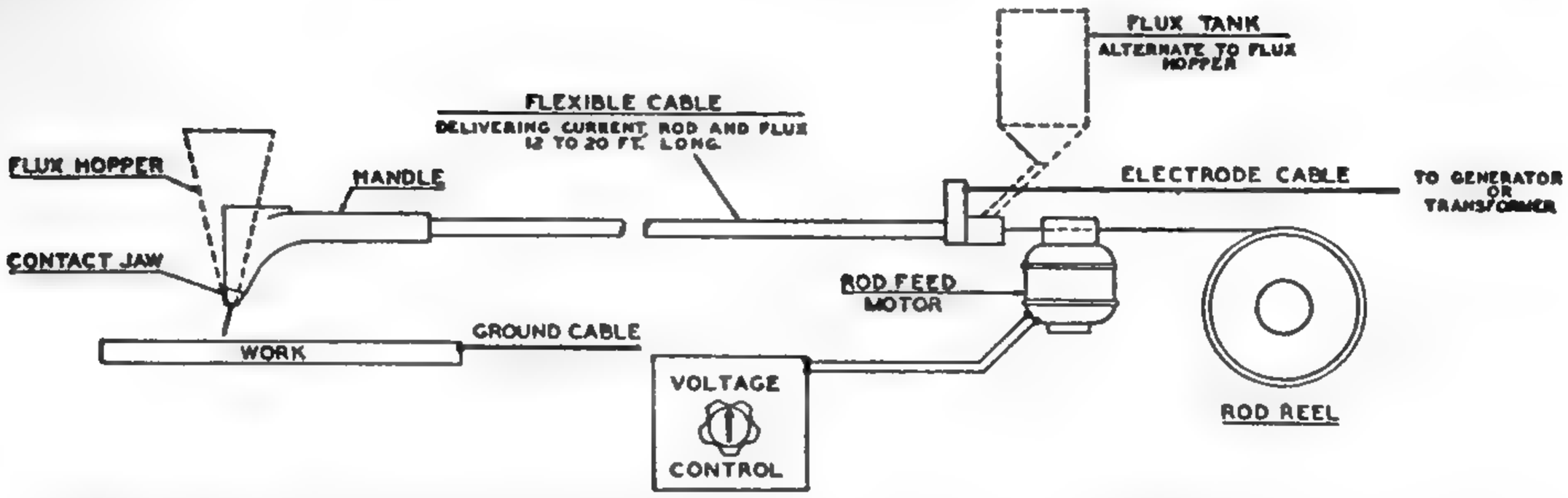


Fig. 12.—Schematic Drawing of Typical Semi-Automatic Submerged Arc Welding Equipment

These fluxes are made to several chemical specifications and several ranges of particle size. The choice will depend upon the welding procedure to be employed, the type of joint and composition of the material to be welded. Alloying elements may be included in the flux to be introduced into the weld metal during welding.

COMMON APPLICATIONS

Materials Which May Be Welded

By far the greatest application of submerged arc welding has been in welding low-carbon steels and high-strength, low-alloy steels. Straight chromium and austenitic chromium-nickel steels are readily weldable in all thicknesses. The welding of columbium-stabilized, chromium-nickel steel is limited to thicknesses in excess of 1/4 inch. Higher alloy, air-hardening steels are generally more readily welded with this than with other processes, although special procedures using preheat, postheat, and special welding techniques may be necessary.

Nonferrous alloys such as nickel, Monel, Inconel and copper-nickel, and the copper-silicon alloys are welded with suitable techniques and materials. Under favorable conditions, copper can be successfully welded. Experimental work indicates the possibility that aluminum can also be welded.

Industrial Uses

Welds made by this process meet the rigid requirements of the ASME Boiler Code for power boilers and for Paragraph U-68 pressure vessels, and are accepted by various insurance and inspection agencies. They are approved for many ship-welding applications by the American Bureau of Shipping, U.S. Coast Guard, by Lloyd's Register of Shipping and by the U.S. Navy.

Following are some of the industries that find use for submerged arc welding: Automotive (Chapter 54); Aviation (Chapter 55); Pressure vessels and boilers (Chapter 51); Surfacing and Maintenance (Chapter 21); Domestic appliances; Earth moving, grading and construction equipment; Machinery (Chapter 49); Electrical; Ordnance; Piping and accessories (Chapter 56); Railroad (Chapter 53); Shipbuilding (Chapter 52); and Structural Weldments (Chapters 47 & 48).

Table 1—Shrinkage in Submerged Arc-Welded Joints

Type of Weld	Average Transverse Shrinkage per Joint, Inches per Joint
Fillet Weld	
Web member joined to plate 5/16 to 9/16-in. thick	
One continuous fillet weld (leg size from 1/4 to 7/16 in.)	0.0065
Two continuous fillet welds (leg size from 1/4 to 3/8 in.)	0.0130
Butt Weld	
Single-Vee butt joint (no root opening), 1/4 to 9/16-in. thick	0.012
Double-welded square butt joint (no root opening), 1/4 to 1-in. thick	0.024

Type of Weld	Average Longitudinal Shrinkage per Joint, Percent of Length
Single-pass butt weld or one continuous fillet weld	0.016
Double-welded butt joint or two full continuous fillet welds	0.033

Table 2—Results of Weld Tests According to ASME Specifications; Boiler Steels Conforming to ASME, API-ASME Specifications

	SA-201A, S.R.[a]	SA-202A, A.W.[b]	SA-203B, S.R.	SA-204B, A.W.	SA-204B, S.R.	SA-212B, A.W.	SA-212B, S.R.	SA-225A, S.R.	SA-285C, A.W.	SA-285C, S.R.	M-115[c] Fig. S.R.
0.505 All-Weld-Metal Tension Test											
Yield point, psi.	37,000	61,000	.....	66,500	61,000	...	53,400	56,800	54,300	46,700	37,000
Ultimate strength, psi.	66,000	87,500	82,600	87,000	82,000	...	78,300	77,700	72,000	67,300	62,000
Elongation in 2 in., %	34.0	21.5	27.5	23.0	27.5	...	30.0	31.0	30.0	33.5	34.0
Reduction in area, %	53.3	36.0	42.5	56.5	58.0	...	58.6	59.6	59.0	62.0	60.4
Transverse Tension Test											
Yield point, psi.	45,300	...	55,000	...	...	54,800	38,100	...	...	...	35,200
Ultimate strength, psi.	69,300	...	78,400	...	...	79,800	73,900	...	...	...	61,700
Failure	In weld	...	In plate	...	...	In weld	In plate	...	...	...	In weld
Free Bend Test											
Elongation, %	53.5	...	66.7	...	...	22.5	51.4	...	...	...	39.3
Hardness											
Brinell	...	...	...	...	...	166	146	...	145	120	...

[a] S.R., stress relieved. [b] A. W., as-welded. [c] ICC-AAR specifications.

Table 3—Typical Mechanical Properties of Welds in Carbon and Low-Alloy Steels

	Cor-Ten, A.W.[a]	Cor-Ten, S.R.[b]	Yoloy, A.W.	Yoloy, S.R.	Mayari R, A.W.	Mayari R, S.R.	Man-Ten., A.W.	Man-Ten., S.R.	0.45 Carbon, 1.25 Mn, A.W.	S.R.	NAX, A.W.	Hi-Steel, A.W.
0.505 All-Weld-Metal Tension Test												
Yield point, psi.	58,500	51,000	52,000–75,000	49,000–67,000	67,000	63,400	63,150	61,000	...	...	...	...
Ultimate strength, psi.	81,500	75,000	75,000–109,000	71,000–90,000	91,800	83,600	89,100	84,000	...	...	...	...
Elongation in 2 in., %	23.0	27.5	26.0–14.5	30.0–25.5	24.0	25.3	22.6	29.5	...	...	...	...
Reduction in area, %	50.8	61.1	55.0–21.0	63.0–23.0	49.7	57.3	55.6	62.0	...	...	...	...
Transverse Tension Test												
Yield point, psi.	55,400	55,700	...	...	...	...	...	...	...	...	48,800	56,740
Ultimate strength, psi.	80,220	76,740	...	...	...	...	...	...	103,500	89,600	72,400	72,830
Break	...	...	...	...	...	...	...	...	Weld	Weld	Base-metal	Base-metal
Free Bend Test												
Elongation, %	36.0	...	...	...	...	...	...	...	25.0	36.0	...	37.0
Hardness												
Parent metal, Rb	81	77	...	...	...	...	92	...	...	...	85	84
Weld metal, Rb	88	80	...	...	...	...	87	...	31Rc	26Rc	93	82
Heat-affected zone, Rb	85	79	...	...	...	...	93	...	...	...	89	84

[b] S.R., stress relieved. [a] A.W., as-welded.

Table 4—Fatigue Properties of Submerged Arc Welds (Rotating Beam)

Weld No.[a]	Condition	Ultimate Strength, Psi.	Yield Point, Psi.	Elongation in 2-In., %	Reduction in Area, %	Charpy impact, Ft.-Lb.[b]	Limiting Stress 10,000,000 Reversals, Psi.
1	A.W.[c]	62,700	43,000	30.7	57	36.5	32,000–35,000
1	S.R.[d]	59,200	35,000	35.5	66	33.5	32,000–35,000
1	N[e]	54,700	32,700	39.0	67.5	36.8	32,000–35,000
2	A.W.	68,200	47,100	28.7	51.5	25.8	35,000–38,000
2	S.R.	63,000	37,700	33.7	63.8	31.2	35,000–38,000
2	N	60,250	38,200	35.8	64	32.5	35,000–38,000

[a] Weld No. 1, rimmed steel, ·2 in. thick (ASTM A-285C). Weld No. 2, silicon-killed steel, 25/16 in. thick (ASTM A-201A).
[b] Charpy Impact Tests made at room temperature using Keyhole Notch.
[c] A.W., as-welded.
[d] S.R., stress relieved.
[e] N, normalized.

Table 5—Typical Mechanical Properties of Welds in Stainless Steel

	AISI Type 304, 7/8 In. Thick		AISI Type 347, 3/4 In. Thick		AISI Type 309 SCB, 3/8 In. Thick,	AISI Type 430, 1/2 In. Thick,
	A.W.[a]	W.Q. 1950° F.[b]	A.W.	S.R., 1550° F.[c]	A.W.	H.T.[d]
0.505 All-Weld-Metal Tension Test						
Yield point, psi.	41,000 43,500	31,000 44,000	43,900 45,000	37,500	41,800	59,700
Ultimate strength, psi.	83,000 84,800	83,000 97,500	83,400 84,500	87,000	80,000	75,700
Elongation in 2 in., %	51 55	49 58	38 41	46	45.3	28.0
Reduction in area, %	60 62	43 65	44 52	69	54.5	...
Transverse Tension Test						
Yield point, psi.	.....	.....	.....	....	.....	37,500
Ultimate strength, psi.	.....	.....	.....	....	.....	72,000
Failure	.....	.....	.....	.....	...	Base metal
Free Bend Test						
Elongation, %	43 52	49 54	40	....	60	70.7
Hardness						
Rockwell	.....	.....	.....	.....	.....	Rb 82-84
Charpy Impact[e]						
Notch in Center of Weld						
Room temp., ft.-lb.	38	36	31	28	32	.....
—320° F., ft.-lb.	26 30	28	17	17	.....	.....
Notch in Heat-affected Zone						
Room temp., ft.-lb.	55	50 63	41	36	.....	.....
—320° F., ft.-lb.	36 42	41-47	47	27	.....	.....

[a] A.W. as-welded.
[b] W.Q., water quenched.
[c] S.R., stress relieved.
[d] H.T., Heat treat at 1425° F. for 4 hr. and slow cool.
[e] Each value average of 3 to 9 tests. 10 ×10 mm. Specimens prepared according to Par. U-142 of ASME Boiler Code.

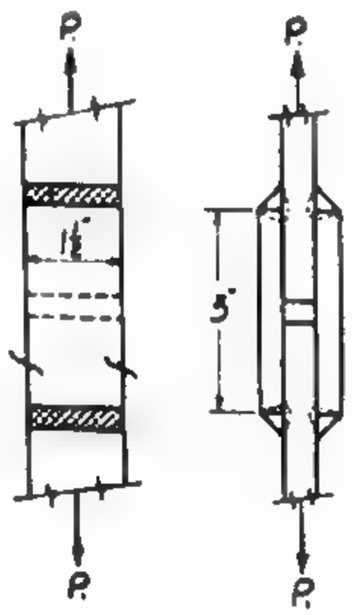
Table 6—Typical Mechanical Properties of Welds in Nickel Alloys

	Nickel	Monel	Cupro-nickel	Inconel, In. 1/4	Inconel, In. 1/16	Hastelloy, Alloy B A W.	Hastelloy, Alloy B Annealed
0.505 All-Weld-Metal Tension Test							
Yield point, psi.	.....	29,000	.....	.....	.....	..	.....
Ultimate strength, psi.	57,200	68,200	.....	.....	.....	.....	.....
Elongation in 2-in., %	36.4	48.0	.....	.....	.....	.....	.....
Reduction in area, %	.....	58.0	.....	.....	.....	.....	.....
Transverse Tension Test							
Yield point, psi.	.....	.....	.....	35,600	45,100	55,000	57,000
Ultimate strength, psi.	59,600	.....	51,600	84,400	83,900	104,000	115,000
Failure	.....	.....	.....	In weld	In weld	.....	.....
Free Bend Test							
Elongation, %	35.3	.....	47.0	.....	.....	16	22
Remarks	Bent flat, no failure	.....	Bent flat, no failure (root bend 55%)	.....	.....	.....	.....
Impact Tests,[a] Test temperature							
+20° C., ft.-lb.	75.6	42.8	.....	.....	.....	.....	.....
−78° C., ft.-lb.	55.7	38.6	.....	.....	.....	.....	.....
−183° C., ft.-lb.	61.4	40.3	.....	.....	.....	.....	.....

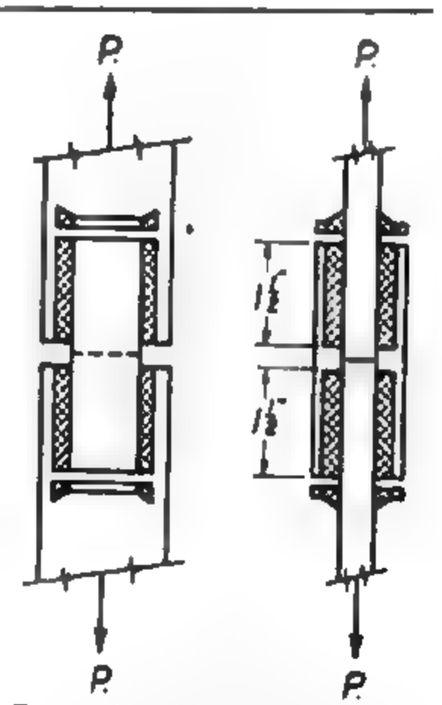
[a] 10-mm. Charpy Keyhole Notch Specimen.

Table 7—Strength of Non-Positioned Fillet Welds

Specimen	Fillet Size,[a] In.	Breaking Load, "P", Lb.	Weld Load, Lb./Linear Inch	Fracture
		Transverse Shear Tests		
1	5/16	69,000	23,000	In weld
2	5/16	71,000	23,700	In weld
3	3/8	72,000	24,000	In weld
4	3/8	73,000	24,300	In weld
		Longitudinal Shear Tests		
1	5/16	97,000	16,200	In weld
2	5/16	94,000	15,700	In weld
3	3/8	104,000	17,300	In weld
4	3/8	100,000	16,700	In weld



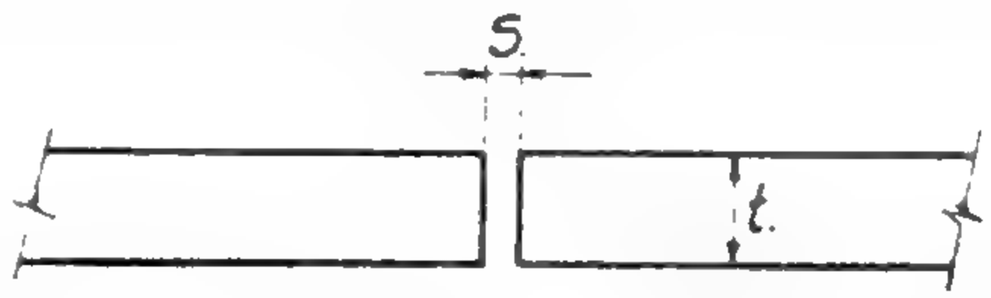
Transverse Shear



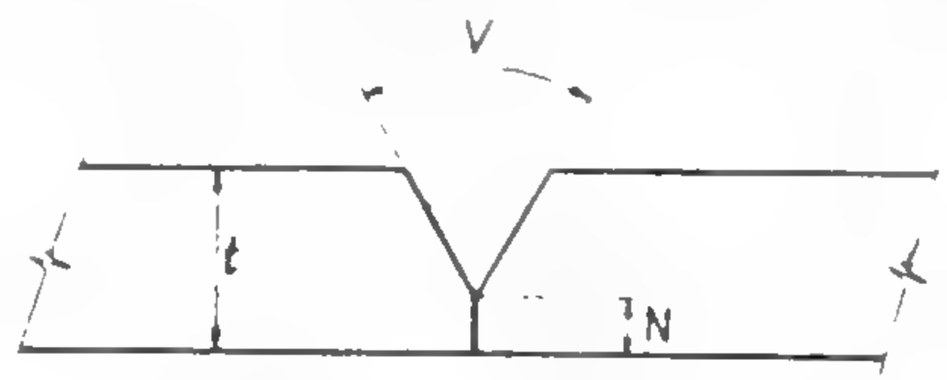
Longitudinal Shear

[a] Fillet sizes given are from measurement of vertical leg.

Table 8—Single-Pass Groove Welds in Medium Carbon Steel with Copper Backing



Thickness, *t*, In	Root Opening, *S*, In	Current, Amp	Voltage, Volts	Speed, In./Min	Electrode Diam., In.	Electrode Lb./Ft. of Weld
10 ga.	0–1/32	250–350	22–24	100–150	3/32–1/8	0.015–0.020
14 ga.	0–1/32	325–400	24–26	100–120	3/32–1/8	0.020–0.025
12 ga.	0–3/32	350–500	24–30	75–120	1/8	0.027
10 ga.	0–1/16	575–650	24–31	60–100	1/8	0.05
3/16	1/16	575–700	25–31	40–65	5/32	0.07
1/4	1/8–3/32	750–850	25–35	30–40	3/16–7/32	0.10
5/16	0–3/32	800–900	26–36	26–30	3/16–7/32	0.25

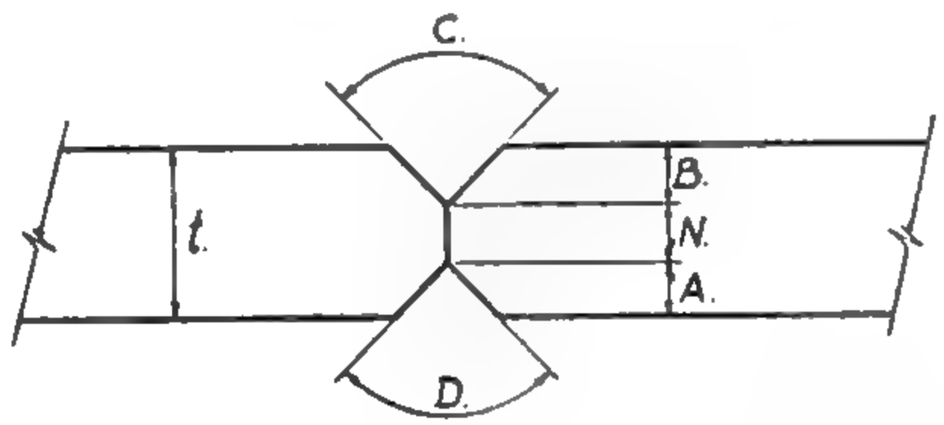


Thickness, *t*, In	Groove Angle, *V*, Deg	Root Face, *N*, In	Current, Amp	Voltage, Volts	Speed, In./Min	Electrode Diam., In.	Electrode Lb./Ft. of Weld
1/4	50–60	0–1/8	625–825	25–32	28–50	5/32–3/16	0.10–0.23
3/8	40–60	0–1/8	900–1100	28–36	24–47	1/4	0.16–0.35
1/2	60	3/16	1075–1175	31–37	19–23	1/4	0.38–0.45
3/4	45	3/16	1200–1300	32–39	12–14	1/4	0.60–0.75
1	35	1/8	1500–1600	35–41	10–12	5/16	0.90–1.10
1 1/4	30	1/8	1600–1700	37–41	8–9	5/16	1.25–1.60
1 1/2	30	1/8	1900–2000	38–43	7–8	3/8	1.85–2.00

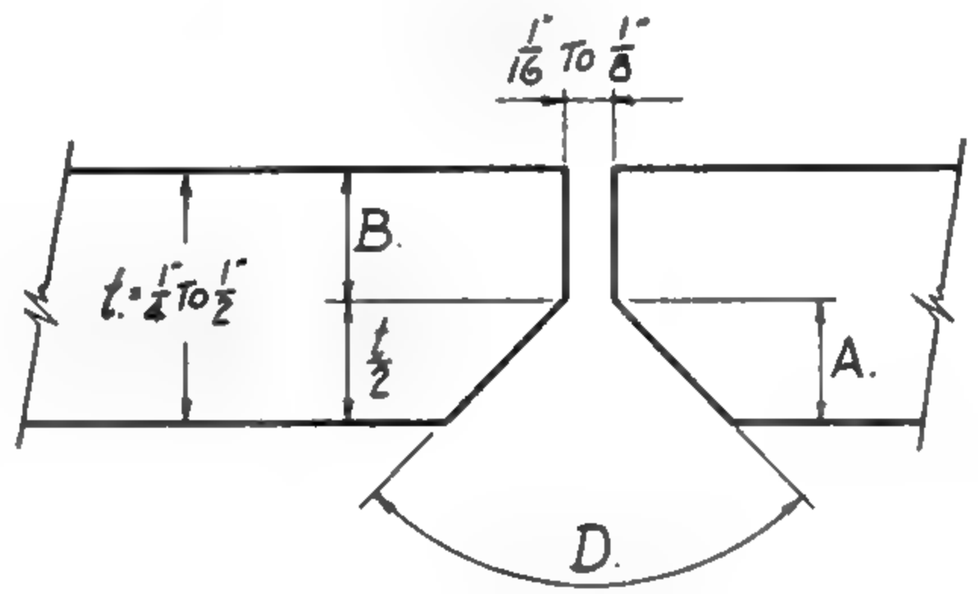
Table 9—Double-Vee Groove Welds in Medium Carbon Steel

	Finishing Pass							Backing Pass						
Thickness, *t*, In.	Depth of Groove *B*, In.,	Groove Angle, *C*, Deg.	Current, Min., Amp.	Voltage, Max., Volts	Speed, In./Min.	Electrode Diam., In.	Root Face, N, In.	Depth of Groove, A, In.	Groove Angle, D, Deg.	Current, Min., Amp.	Voltage, Max., Volts	Speed, In./Min.	Elec- trode Diam. In.	Electrode Consumption, Lb./Ft. of Joint
3/4	3/8	60	1000	36	16	7/32	1/4	1/8	60	700	35	22	7/32	...
	1/4	90	1150	35	13	1/4	5/16	3/16	90	850	33	16	1/4	0.85
1	3/8	60	1050	36	12	7/32	1/4	3/8	60	900	35	14	7/32	...
	3/8	90	1300	36	11	1/4	5/16	5/16	90	1000	34	15	1/4	1.10
1 1/4	5/8	60	1100	37	7.5	7/32	1/8	1/2	60	1000	35	12	7/32	...
	1/2	70	1450	36	10	5/16	3/8	3/8	60	1100	35	13	1/4	1.44
1 1/2	3/4	60	1100	37	6.5	7/32	1/8	5/8	60	1050	36	9	7/32	...
	5/8	70	1600	37	9	5/16	7/16	7/16	60	1300	35	10	1/4	1.96
1 3/4	11/16	80	1800	38	7	5/16–3/8	7/16	5/8	60	1450	35	8	5/16	2.76
2	3/4	80	1850	38	6	5/16–3/8	1/2	3/4	70	1500	35	7	5/16	3.68
2 1/4	7/8	80	1850	39	5	5/16–3/8	5/8	3/4	70	1600	36	6	5/16	4.62

(See Table 9)



(See Table 10)



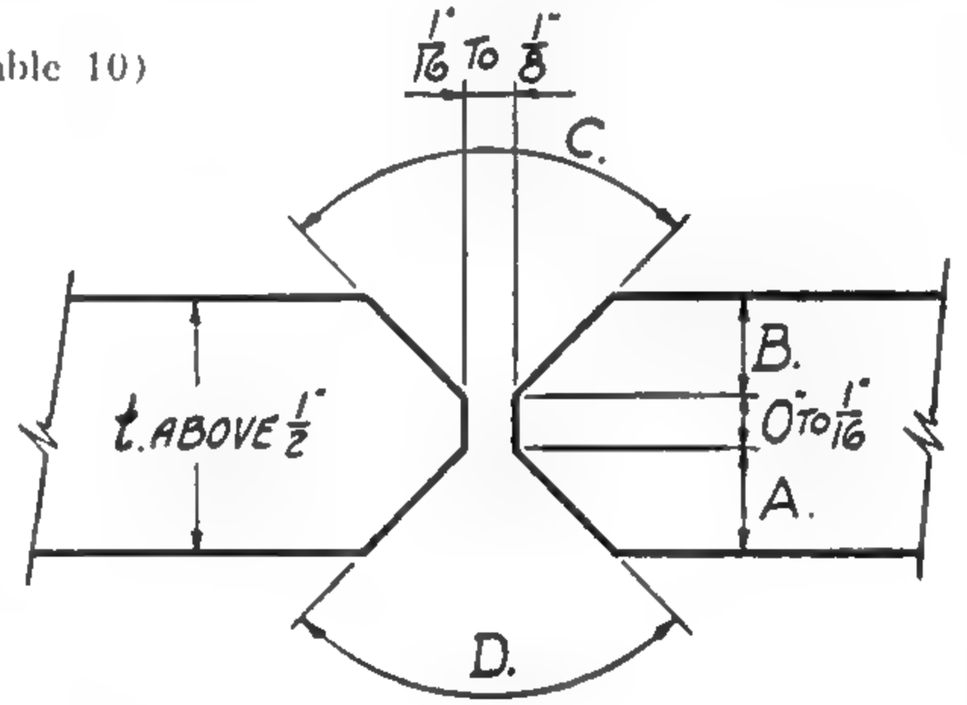
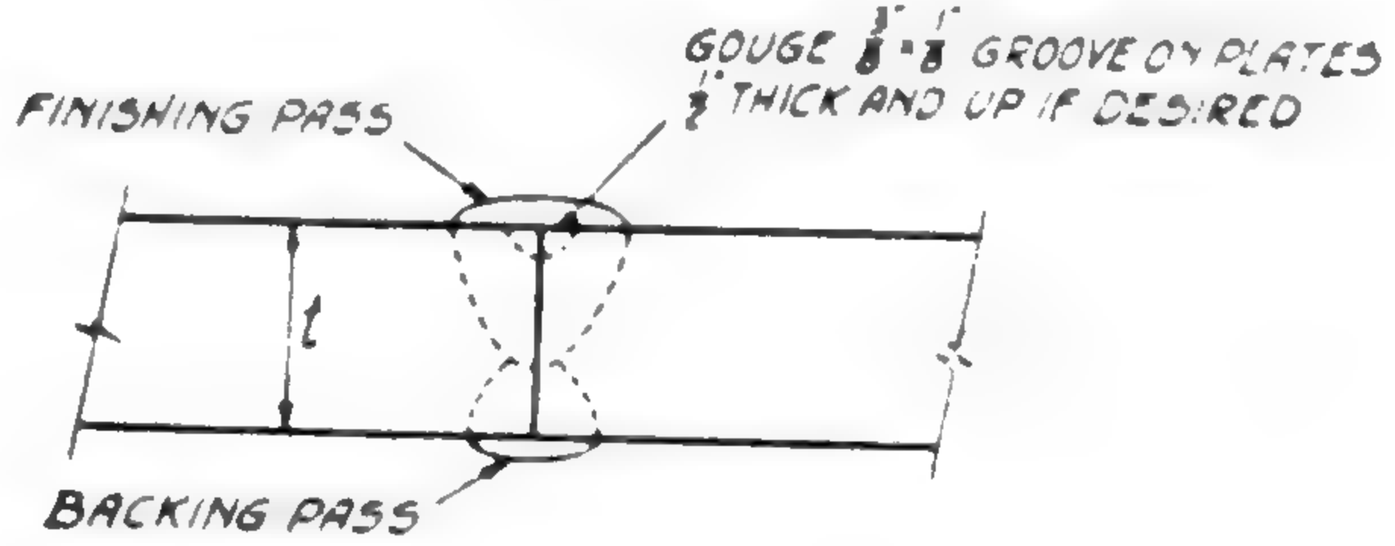


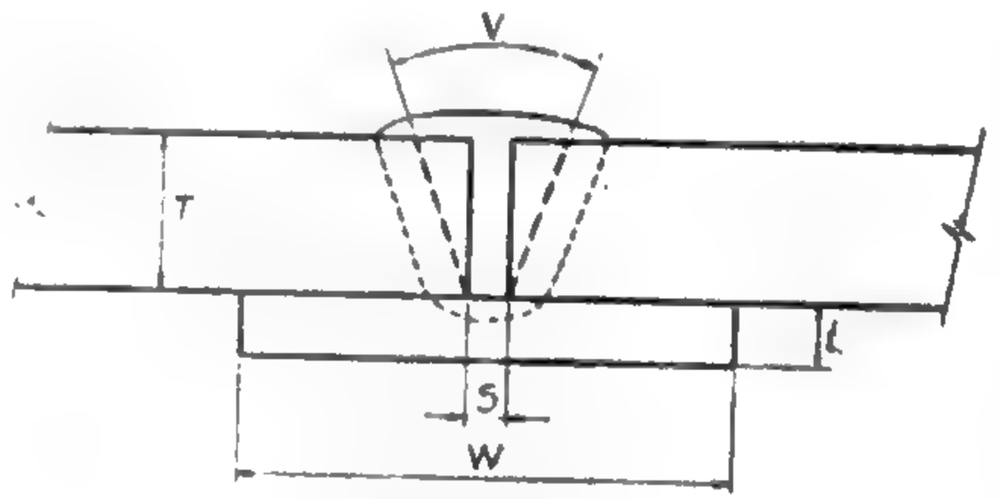
Table 10—Double-Vee Groove Welds with Manual Backing Weld

			Submerged Arc-Weld			Electrode		Manual Backing Weld	
Thickness, *t*, In.	Root face, *B*, In.	Groove Angle, *C*, Deg.	Current, Amp.	Voltage, Volts	Speed, In./Min.	Diam., In.	Lb./Ft. of Pass	Depth of Groove, *A*, In.	Groove Angle, *D*, deg.
1/4	1/8	0	550–575	28 33	27–48	5/32–7/32	0.13	1/8	90
3/8	3/16	0 60	700–800	33 35	18 30	3/16–7/32	0.18	3/16	90
1/2	1/4	0 60	850–950	33 36	16–27	3/16–7/32	0.30	1/4	90
3/4	5/16	60 90	900–1050	35	12–18	1/4–7/32	0.50–0.57	3/8	90 or U
1	9/16	60–70	1050–1250	35 37	9–11	1/4–7/32	0.85–0.95	3/8	90 or U
1 1/4	11/16	70	1450	37	9	5/16		1/2	U
1 1/2	13/16	70	1650	37	9	5/16		5/8	U
1 3/4	15/16	70	1700	38	8	5/16		3/4	U
2	1	80	1850	38	6	5/16		15/16	U
2 1/4	1	80	1850	38	6	5/16		1 3/16	U

Table 11—Two-Pass Groove Welds

Thickness, t, In.	Root Opening, S, In.	Groove Angle, α, Deg	First Pass			Backing Pass			Electrode Consumption, Lb./Ft. of Joint
			Current, Amp	Voltage, Volts	Speed, In./Min	Voltage, Volts	Speed, In./Min	Electrode, Diam., In.	
1/4	0	45	850	34	20	30	28-48	5/32	0.22
5/16	0	45	950	34	20	32	28-32	5/16 7/32	0.24-0.32
3/8	0	45	950	34	20	32	22-32	5/16 7/32	0.35-0.52
1/2	0	45	950	34	20	34	20-24	5/16 7/32	0.43-0.57



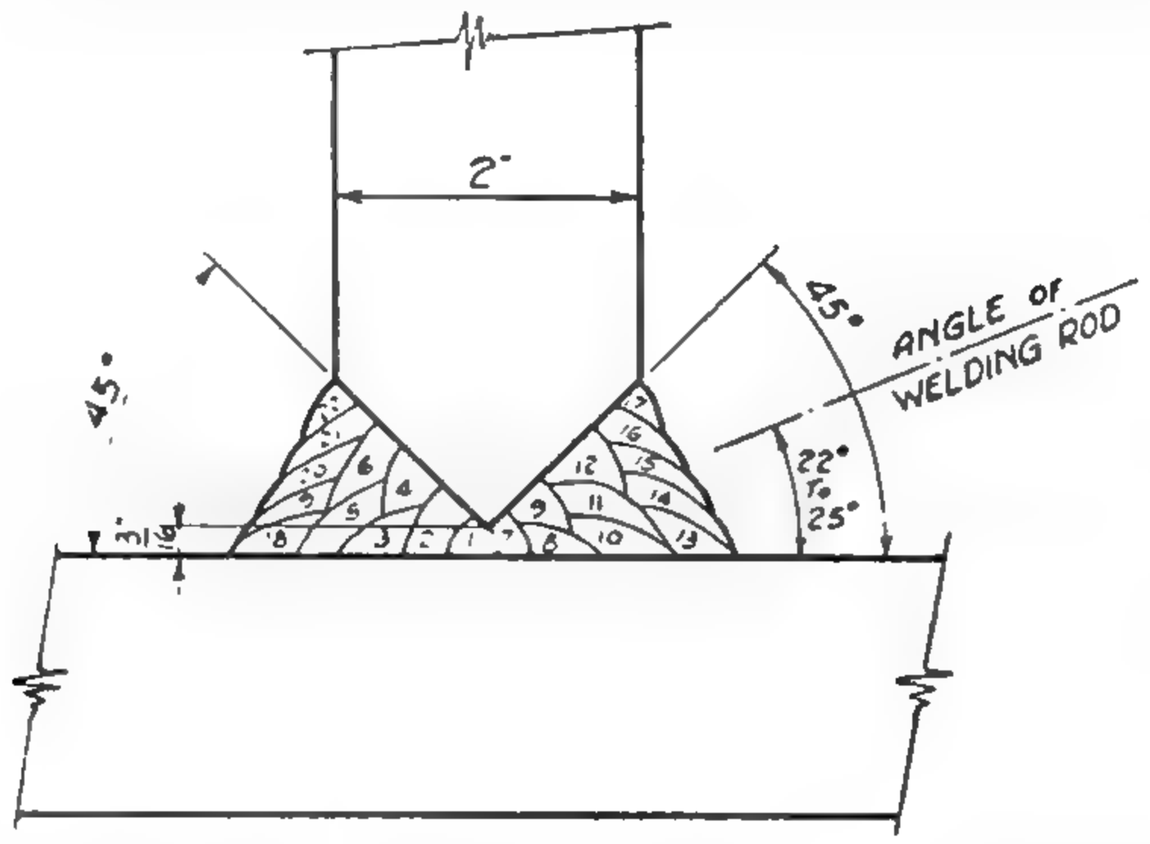


(See Table 12)

Table 12—Groove Welds with Steel Backing

Thickness, T, In.	Root Opening, S, In.	Groove Angle, α, Deg	Current, Amp	Voltage, Volts	Speed, In./Min	Electrode Diam., In.	Lb./Ft. of Joint	Backing Bar, In. t, Min.	Backing Bar, In. W, Min.
16 ga.	0-1/16		150				0.020	14 ga.	3/8
14 ga.	0-1/16		150				0.030	12	3/8
12 ga.	0-1/16		150				0.037	12	1/2
3/16	0-1/16		650				0.070	1/8	5/8
1/4	1/16-3/16	45	850	34	30	5/32	0.150	3/16	3/4
5/16	1/16-3/16	45	950	34	30	5/32	0.210	1/4	1
3/8	1/16	45	950	34	30	5/32	0.25-0.32	1/4	1
1/2	1/16	45	950	34	30	5/32	0.42-0.66	3/8	1
5/8	1/16	45	950	34	30	5/32	0.87-1.10	1/2	1 1/4

Table 13—Double-Vee Groove Welds in Tee Joints[a]

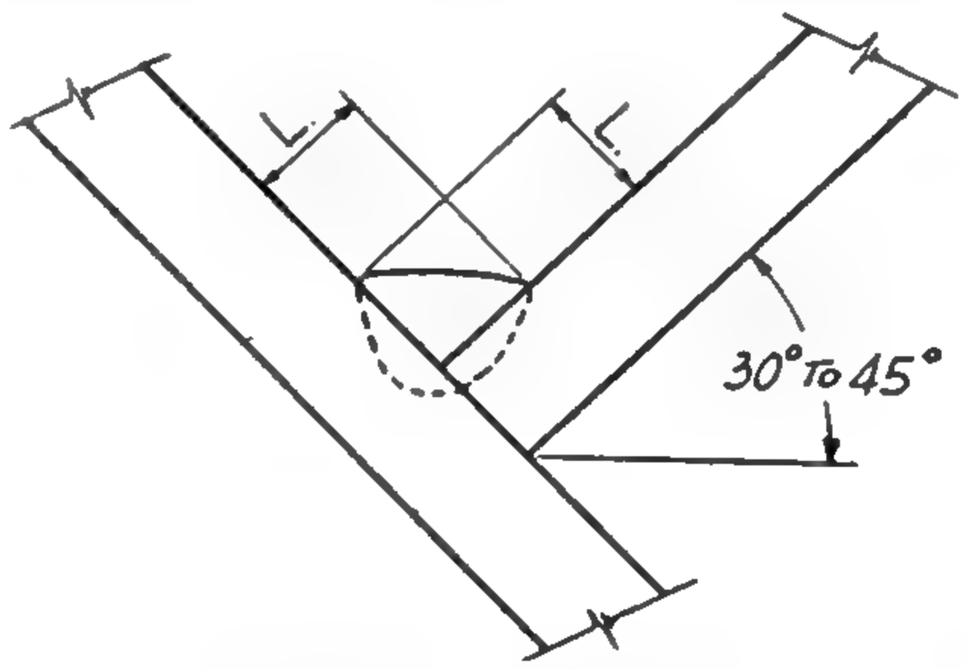


Pass No.		Current, Amp.	Voltage, Volts	Speed, In./Min.	Pass No.		Current, Amp.	Voltage, Volts	Speed, In./Min.
1	1st Side[b]	550	28	14	12	2nd Side	600	28	20
2		600	28	10	13		600	28	14
3		600	28	10	14		600	28	14
4		600	28	20	15		600	28	14
5		600	28	10	16		600	28	16
6		600	28	18	17		600	28	24
7	2nd Side	600	28	10	18	1st Side	600	28	16
8		600	28	12	19		600	28	16
9		600	28	18	20		600	28	16
10		600	28	14	21		600	28	18
11		600	28	14	22		600	28	28

[a] These data are suitable for 2-in. web plate; similar preparation and welding conditions can be used for any thickness.

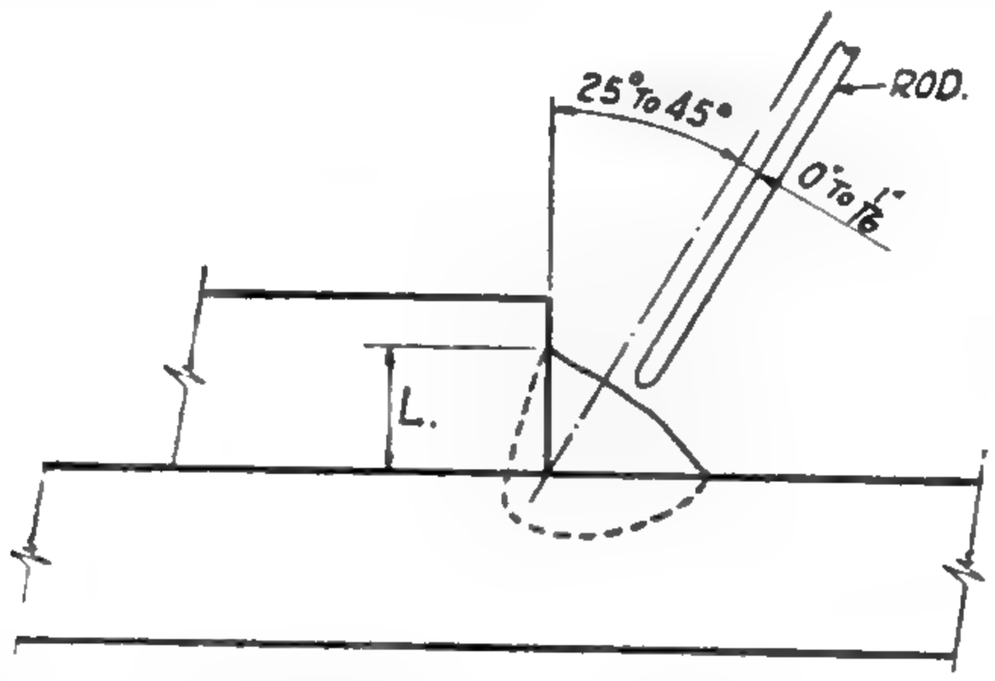
[b] Backing weld may also be made manually.

Table 14—Fillet Welds in the Flat Position



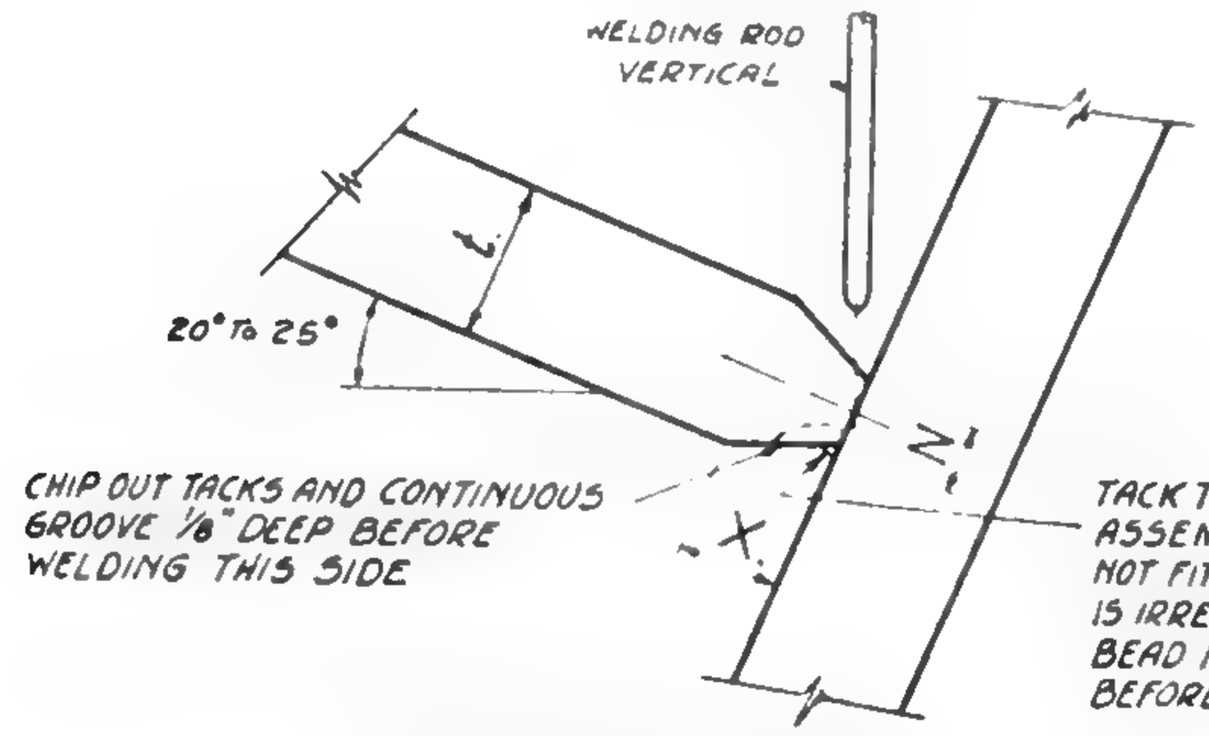
Weld Size, *L*, In.	Current, Amp.	Voltage, Volts	Speed, In./Min.	Electrode	
				Diam., In.	Lb./Ft. of Weld
1/8	375–400	25	36–55	1/8	0.04
3/16	500–550	27–28	32–42	5/32	0.07
1/4	625–650	27–30	28–36	5/32	0.11
5/16	650–700	28–33	22–24	5/32	0.17
3/8	750–1000	29–35	18–26	3/16–7/32	0.25
1/2	850–1000	31–35	13–15	1/4–7/32	0.43
5/8	950–1050	31–35	9–10	1/4–7/32	0.66
3/4	1050–1080	31–35	7–8	1/4–7/32	0.95
1	1100	35	4–5	7/32	1.72

Table 15—Fillet Welds in the Horizontal Position



Weld Size, *L*, In.	Current, Amp.	Voltage, Volts	Speed, In./Min.	Electrode — Diam., In.	Electrode — Lb./Ft. of Weld
1/8	350–375	25	28–55	1/8	0.06
3/16	400–550	26–28	22–42	1/8–5/32	0.09
1/4	450–625	26–30	20–36	1/8–5/32	0.14
5/16	500–700	27–33	18–26	5/32	0.20
3/8	600–750	25–33	15	5/32	0.29

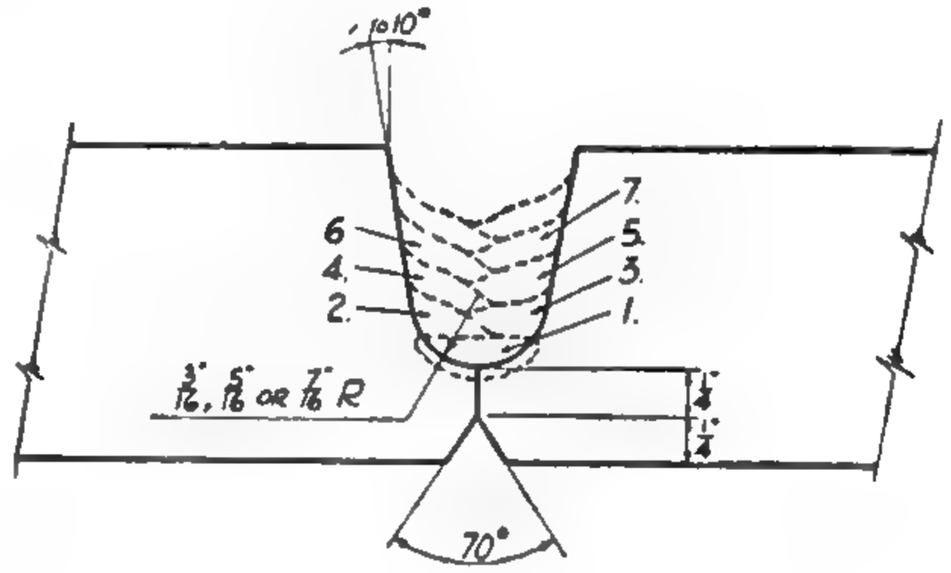
Table 16 Fillet Welds in the Flat Position Made With Edge Preparation



t, In.	*N*, In. ±1/16	*X*, In. ±1/16	Welding Rod — Diam., In.	Welding Rod — Lb./Ft.		Current, Amp.	Max. Voltage, Volts	Speed, In./Min.
5/8	1/4	3/8	3/16	0.56	First weld	750	30	9
					Final weld	800	30	7
3/4	3/8	1/2	1/4	0.72	First weld	950	30	8.5
					Final weld	1050	30	8.5
1	7/16	5/8	1/4	1.33	First weld	1050	30	8
					Final weld	1150	30	7.5
1 1/4	7/16	3/4	1/4	2.75	First weld	1100	30	7
					Final weld	1150	30	7
1 1/2	7/16	7/8	1/4	3.00	First weld	1150	30	6.5
					Final weld	1200	30	6

Table 17—Multiple-Pass Groove Welds

Pass No.	Current, Amp.	Voltage, Volts	Speed, In./Min.	Electrode Diam., In.
1	400-600	27-30	8-24	3/16-1/4
2	500-800	27-33	8-24	3/16-1/4
3	600-900	27-33	8-12	3/16-1/4
Subsequent passes	600-900	27-33	8-24	3/16-1/4
Final passes	600-900	33-35	6-18	3/16-1/4



NOTE: Electrodes can be centered for all passes on groove designed with zero deg. bevel angle and 7/16 in. radius.

Electrode generally centered only on first four passes on grooves designed with beveled side walls. Remaining passes deposited on alternate sides of groove.

Table 18—Plug Welds

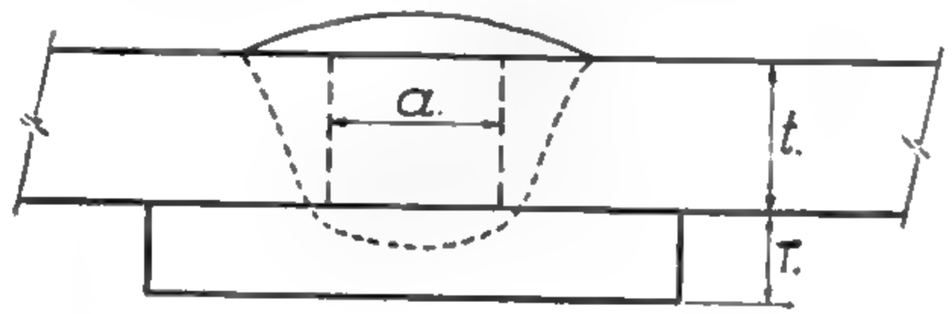


Plate Thickness, In. t	Min. T	Hole Size, a, In.	Current, Amp.	Voltage, Volts	Time/Plug, Sec.	Electrode Diam. In.	Electrode Deposit, In.	Lb./Plug, Approximate	Shear Area[a] Sq. In.
1/4	3/16	5/16	800	25	..	3/16	0.8	0.006	0.11
	5/16	3/4	650	27	6	3/16	3.5	0.027	0.44
3/8	5/16	9/16	900	27	5	1/4	2.2	0.031	0.25
	3/8	13/16	900	27	10	1/4	4.6	0.064	0.52
1/2	7/16	11/16	900	27	9	1/4	4.3	0.060	0.37
	1/2	15/16	900	28	15	1/4	7.0	0.098	0.79
5/8	1/2	13/16	900	28	15	1/4	7.5	0.105	0.52
	1/2	15/16	900	28	21	1/4	10.0	0.140	0.79
3/4	1/2	13/16	1000	30	18	1/4	9.2	0.128	0.60
	1/2	1 1/16	1200	30	24	1/4	15.6	0.218	1.28
1	5/8	1	1200	30	35	5/16	15.0	0.326	1.10
1 1/4	5/8	1	1200	30	38	5/16	14.5	0.370	1.10
1 1/2	5/8	1	1300	30	40	5/16	20.0	0.435	1.28

NOTE: Lower or higher welding current with longer or shorter time may be used, depending on thickness, *T*. It is important to stop electrode feed motor and allow electrode to melt off 1 to 2 sec. before interrupting welding current, in order to avoid center depression on surface of plug.

[a] These values are actual and include penetration beyond root.

BIBLIOGRAPHY

1. *Welding in Tanker Construction,* T. M. Jackson, The Welding Journal, October 1937; The Welding Engineer, November 1937.

2. *Welded Steel Pipe for the City of Toronto Water Works Extension,* C. R. Whittemore, The Engineering Journal (Canadian) July 1938.

3. *Single-Pass Electric Welding of Unfired Pressure Vessels,* R. H. Wallace, The Welding Journal, January 1939.

4. *Pressure Aqueduct for Boston,* K. R. Kennison, Engineering News-Record, August 31, 1939.

5. *Extension of Fusion Welding in Special Pipe and Pipe Fitting Applications,* E. Hall Taylor, The Welding Journal, February 1940.

6. *Automatic Welding in the Construction of Diesel-Electric Locomotives,* J. H. Hruska, The Welding Journal, February 1940.

7. *Tank Top Welded by Unionmelt,* F. J. Deemer, Marine Engineering and Shipping Review, January 1941.

8. *Automatic Arc Welding in Ship Construction,* F. G. Outcalt and J. M. Keir, Iron Age, January 22, 1942.

9. *Versatile Carriage Speeds Automatic Welding,* Electrified Industry, June 1942.

10. *The Unionmelt Welding Process,* Automotive and Aviation Industries, November 1942.

11. *Anchor Chains—Are Now Electric Welded by Unionmelt Method,* H. W. Young, Steel, January 18, 1943.

12. *Adapting Automatic Electric Welding to Routine Production,* J. M. Keir, The Welding Journal, March 1943.

13. *Automatic Welding of Pipe Flanges,* F. L. Alexander, L. Hunt and John Logan, Pacific Marine Review, March 1944.

14. *Automatic Welding for Victory Ships,* M. H. MacKusick, Western Metals, July 1944.

15. *Marine Steam Turbine Design,* R. C. Allen, Marine Engineering and Shipping Review, October 1944.

16. *Special Setups Speed Automatic Welding of Masts and Kingposts,* G. Eldridge Stedman, Steel, February 26, 1945.

17. *Submerged Arc Welding Steps Up Production of Invasion Boat Assemblies,* Industry and Welding, April 1945.

18. *Continuous Welding of Tubular Containers,* R. V. Anderson, Machinery, May 1945.

19. *Magnetic Holddown Chucks Facilitate Plate Welding,* Cyril Provo Hubert, The Iron Age, July 19, 1945.

20. *Composite Generator Frames,* G. W. Birdsall, Steel, October 22, 1945.

21. *Butt Welding of Heavy Sections—An Application of the Submerged Arc Process,* R. R. Sillifant, Welding, January 1946.

22. *High-Quality Tank Manufacture,* W. P. Hindman, Machinery, January 1946.

23. *Rebuilding Locomotive Wheels by Automatic Shielded Arc Methods,* L. K. Stringham, The Welding Journal, April 1946.

24. *Effect of Weld Length Upon Residual Stresses of Unrestrained Butt Welds,* E. Paul DeGarmo, J. L. Meriam and Finn Jonassen, The Welding Journal Res. Suppl., August 1946.

25. *Stainless Steal Refrigerator Car,* R. E. DeCamp, Western Machinery and Steel World, November 1946.

26. *Fabricating with Automatic Welding,* Steel Processing, February 1947.

27. *Automatic Welding in Steel Plant Maintenance,* H. E. Holman, Iron and Steel Engineer, April 1947.

28. *Depositing Overlaid Surfaces by the Submerged Melt Welding Process,* L. C. Bradburn, J. M. Keir, J. E. Taylerson, The Welding Journal, April 1947.

29. *Jigs and Fixtures for Automatic Fusion Welding,* E. D. Morris and L. J. Berkeley, The Welding Journal, April 1947.

30. *Submerged Melt Welding of Corrosion Resistant Metals,* R. J. Anderson and H. J. Roberts, The Welding Journal, April 1947.

31. *Submerged Melt Welding in Pressure Vessel Fabrication,* N. G. Schreiner, The Welding Journal, May 1947.

32. *Shape Welding by the Submerged-Melt Welding Process,* J. A. Kratz, The Welding Journal, January 1948; The Welding Engineer, January 1948.

33. *Manual Hidden Arc Welding Reduces Labor Costs on Underframe Sub-Assemblies,* J. L. Forand, Railroad Equipment, May 1948.

34. *Manually Operated Hidden-Arc Welding Equipment Applied in Fabricating Machine Tool Members,* E. F. Arntzen and W. Lilly, Machinery, June 1948.

35. *Semi-Automatic Submerged Arc Welding,* Vladimir Peters, Industry and Welding, June 1948.

36. *Manual Use of Hidden Arc Welding Reduces Welding Time on U-68 Code Work by 12 Percent,* E. A. Smith, The Welding Journal July 1948.

37. *Automatic Welding Speeds Up Box Car Production,* C. O. Herb, Machinery, February 1948.

38. *Submerged Arc Welding of Freight Cars,* E. A. Watson, The Welding Journal, October 1948.

CHAPTER 14

STUD WELDING*

FUNDAMENTALS OF PROCESS

Definition and General Description

STUD WELDING is an arc-welding process wherein coalescence is produced by heating with an electric arc drawn between a metal stud, or similar part, and the other work part until the surfaces to be joined are properly heated, when they are brought together under pressure, and no shielding is used.

The pressure exerted is nominal, being provided by the main spring of the stud welding gun, which acts upon and holds the stud in place until the weld is completed. No shielding is provided as in the inert-gas shielded-arc process, but some shielding does result from the use of a ceramic ferrule surrounding the stud, which reduces atmospheric oxidation by limiting free access of air to the stud.

Stud welding is very similar in many respects to manual metal-arc welding. The heat necessary for end-welding of studs is developed by passage of current by an arc from the stud (electrode) to the plate (work) to which the stud is to be welded. The process differs primarily in that establishment of the arc, determination of the welding time, and the final plunging home of the stud to complete the weld are controlled automatically. This eliminates, almost entirely, possible operator inconsistencies from the welding procedure.

Interest in stud welding was first aroused in Naval and other shipbuilding operations where the securing of wood decking to steel plates had been a serious problem since the first steel ships were built. It was evident that if the wood decking could be placed and secured from the top side without drilling the steel deck, the finished job would be more satisfactory than that secured by any method previously devised. It was this one particular application which kept interest alive in stud welding and led directly to stud welding as it is used today.

In the early development stages it was found necessary to maintain a constant arc length, and a consistent weld time, if satisfactory welds were to be obtained with any degree of regularity. It was also found to be an advantage if an arc-stabilizing and deoxidizing flux was used during the welding operation. The first step in this direction was the use of a loose flux which was poured into the hole drilled through the wood decking prior to the insertion of the stud for the welding operation. Since all work was done in the flat position, this procedure worked out fairly well.

It was later found advantageous to use a means of holding the loose flux in place, to keep it from being scattered around under the wood decking before the weld could be made. It also proved necessary to protect the wood itself from charring while the weld was being made. The protection from charring was particularly essential in order to avoid contamination of the weld metal by the products of combustion of the wood and also to overcome the explosive emission of steam resulting from the moisture content of the wood. The answer to this problem was a lava-rock type of shield or ferrule consisting of a simple tube of porcelain-like material. The ferrule was inserted into the drilled hole in the wood decking prior to placing of the flux and insertion of the stud.

Improvement in stud-welding equipment and control methods was slow but

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* Prepared by a committee consisting of R. C. Singleton, Nelson Stud Welding Div., Morton Gregory Corp., *Chairman;* Charles Druetzler, GMC Electro-Motive Div.; A. C. Leigh, The Ingalls Shipbuilding Corp.; C. A. Maxwell, The Babcock & Wilcox Co.; Ted Nelson, Nelson Specialty Corp.; A. J. Raymo, The Baldwin Locomotive Works; Wilson Scott, Westinghouse Electric Corp.; R. F. Wyer, General Electric Co.

steady. By 1937 it was possible to obtain reasonably consistent downhand stud welds with the relatively crude equipment then available. In the years from 1939 to 1941 stud welding progressed tremendously. This was brought about primarily by three factors: (1) The development of the presently used method of loading flux into the end of the stud to permit the use of studs in all welding positions; (2) the development of a stud-welding gun which could be used in all positions; and (3) the development of a spring, chuck and ferrule combination which made it possible and practical to hold the ferrule while the gun was being used to weld studs in all welding positions. These three developments immediately removed the stud welding gun from the category of a highly specialized tool for securing wood decking and changed it into an all-purpose tool which could be used for securing end-welded studs wherever it was necessary or practical for such fastenings to be made.

Basically, the stud welding gun has changed very little since 1943 except for the refinement of the equipment, and further development in design of studs and ferrules. The present day stud welder may be used either as a portable or rigidly-mounted tool, and has been widely accepted in all industries.

Principles of Operation

The stud-welding process involves the same basic principles as any of the other arc-welding processes. Application of the process consists of two steps: (1) Developing heat by drawing an arc between the stud and the plate to which it is to be welded; and (2) bringing the two pieces into intimate contact when the proper temperature is reached.

The present equipment consists of the stud gun, a control unit (timing device), studs and ferrules, and an available source of d.c. welding current. The mechanics of the process are as follows:

The stud is loaded into the chuck, the ferrule is placed in position over the stud and the gun is properly positioned for welding. Then the trigger is depressed, starting the automatic welding cycle. A solenoid coil within the body of the gun is energized lifting the stud, creating an arc and forming a molten pool on the plate and end of stud. When the arcing period, as pre-set in and controlled by the control unit, is completed, the welding current is automatically shut off, de-energizing the solenoid, and allowing the main spring of the gun to plunge the stud into the molten pool on the plate to complete the weld.

Metallurgical Aspects

Ferrous.—The metallurgical problems of stud welding are generally much the same as those encountered in any arc-welding process where the heat of an electric arc is used to melt a portion of the base metal and the electrode in the course of welding. However, improved impact and fatigue properties are obtained because of the complete fusion of base metal. This condition is clearly shown in both macro- and micro-examination. (See Fig. 1.) A typical stud weld macrosection (Fig. 1*b*) shows the weld metal to be pushed toward the perimeter of the stud to form a fillet. A fairly large percentage of the end area of the stud (base metal-unmelted) is touching the base metal of the workpiece. This reduces the amount of weld metal (cast structure) in the joint to a minimum. The various heat-affected zones common to arc welding are present except to a lesser degree due to the short welding cycle. (See Chapter 3—Welding Metallurgy.) Micro-examination of a typical stud weld cross section (Fig. 1*c*) shows that the zones and the microstructures present therein are typical of those found in arc welds made in mild steel

Generally the same restrictions as to the weldability of ferrous materials, which apply to metal-arc welding may also be applied to stud welding. The usual carbon limit for plain carbon steel to be stud welded without preheat is 0.30%. If sections are relatively light, 1/8 in. and under, this limit may be raised somewhat due to the decreased cooling effect. If the section to which the stud is to be welded is heavy, stud welding of higher than 0.30% carbon steel without preheat is a questionable practice. In some instances where the base metal is quite cold the maximum permissible carbon content will be lowered somewhat. While sound welds may be obtained on the higher carbon and alloy steels, the danger of brittleness in the weld or heat-affected zone due to hardness resulting from the quenching action of surrounding metal makes such welding practical under

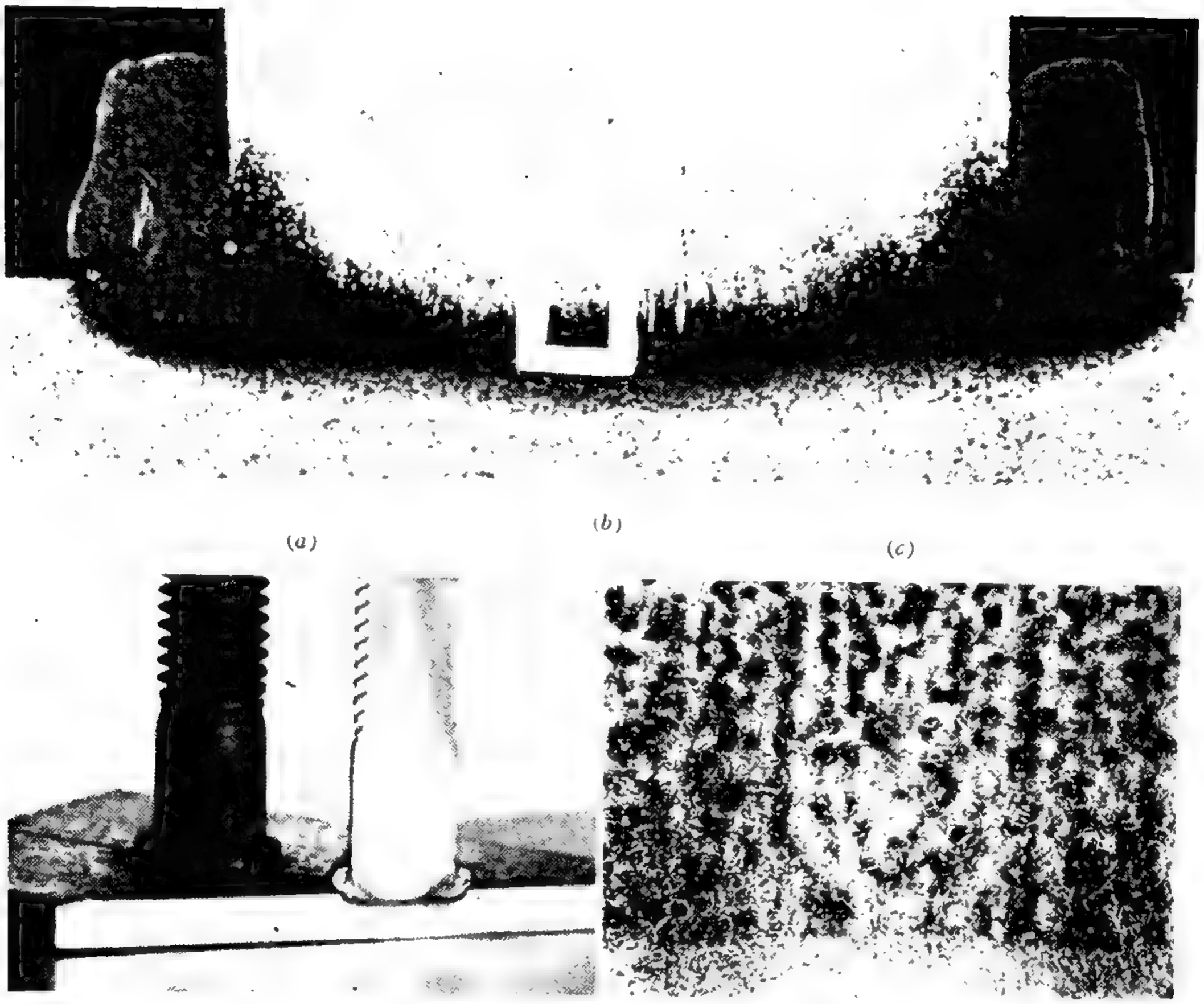


Fig. 1—Typical Stud Weld

(*a*) Section through 1/2-in. diam. stud welded to 1/4-in. plate. Nital etch.
(*b*) Stud weld macrosection. Note small amount of weld metal and complete fusion across base of weld. Nital etch.
(*c*) Stud weld microsection. See (*b*) for section location. Note stud base metal at top, heat-affected zone through the center and the base metal at bottom of field. Nital etch. 125×.

only very special and closely controlled conditions. It should be noted that for mild steel, the section thickness is relatively unimportant as far as weldability is concerned. The most important factor in this respect is that the section thickness be heavy enough to permit the welding of studs without burning through. See Table 1 for minimum recommended plate thicknesses.

If the medium and higher carbon steels are to be stud welded it is imperative that preheat be used in order to prevent cracking through the heat-affected zone. In some instances the combination of preheating and tempering after welding has proved to be very satisfactory.

Stainless steels of all classes may be welded. However, only the austenitic stainless steels are recommended for general application as other types are subject to air hardening and will have brittleness in the weld area unless preheating or tempering is used. The weldable grades include AISI types 304, 307, 309, 310 and 347. Type 304 (18 Cr–8 Ni) is the type most commonly used for stud welding. (See Chapter 31—Austenitic Steels. for analyses of these types.)

Stainless steel studs may be readily welded to stainless steel or to mild steel as the application may require. The welding setup used is the same as that recommended for ordinary steel except for an increased power requirement (about 10%).

The low-alloy, high-tensile steels such as Yoloy, Cor-Ten, N.A.X., Mayari R. Otiscoloy, R.D.S., etc., are satisfactorily stud welded when the carbon content is held to 0.12% maximum. This maximum fits generally the analyses of the above materials where they are supplied for welding and forming operations. If the

carbon content exceeds the above noted maximum, it may be necessary to resort to moderate preheat in order to obtain required toughness in the weld area.

Table 1—Minimum Recommended Plate Thickness[a]

Stud Size (Diam., In.)	Mild Steel, In.	Stainless Steel, (AISI 304), In.
8–32	0.036	....
10–24 (3/16)	0.036	0.036
1/4	0.048	0.048
5/16	0.054	0.054
3/8	0.063	0.063
7/16	0.078	0.105
1/2	0.094	0.135
5/8	0.125	0.156
3/4	0.156	0.250

[a] Thickness necessary to obtain a satisfactory weld without burning through the plate. Full strength of the stud may not be developed under above conditions due to lack of strength in the base plate.

Nonferrous.—Stud welding on brass, bronze, aluminum and chrome-plated material is practical and is being done commercially in the automobile, radio, refrigerator and other industries, while magnesium and some of the Monels have been stud welded under laboratory conditions.

Weld Quality

The modern stud welder is semi-automatic. Dependence upon the skill of the operator has been reduced to a minimum. It is necessary, however, for the equipment to be properly set up and properly used in order to obtain consistently satisfactory results. It is, therefore, essential that the welding operator have a clear conception of what the stud welder should do in the way of producing quality welds. Operators should also be cautioned against variations from standard procedures which may result in erratic results.

The actual mechanics of the inspection or quality control procedure will of course depend upon local circumstances. In all cases the problem will be greatly simplified by proper instruction of the welding operator. The more skilled the operator the less inspection required. This of course is true of all welding processes.

Generally visual inspection of the finished weld is sufficient to indicate whether or not a weld is satisfactory. This procedure is commonly supplemented by a bend test. Questionable welds are checked by bending the stud between 10 to 15 deg. from the vertical and straightening. (The tool used for this bending test is usually a 1-in. diam. rod, 10 to 12 in. long, drilled or tapped on one end to fit the stud.)

It is also considered good practice to weld several studs to a check plate prior to starting production runs. Test studs should be checked visually and also tested to destruction by bending with a hammer. Failure should occur in the stud or base plate outside the weld zone.

Equipment Used

The equipment necessary for stud welding consists of: (1) A stud-welding gun, either portable or fixed (production gun); (2) a control unit to control the time of current flow; (3) a source of d.c. welding current; and (4) studs and ferrules.

Portable Gun

The stud-welding gun (Fig. 2) is a highly portable tool with a tough body made of rag-bakelite plastic, weighing approximately 5 pounds. In appearance the

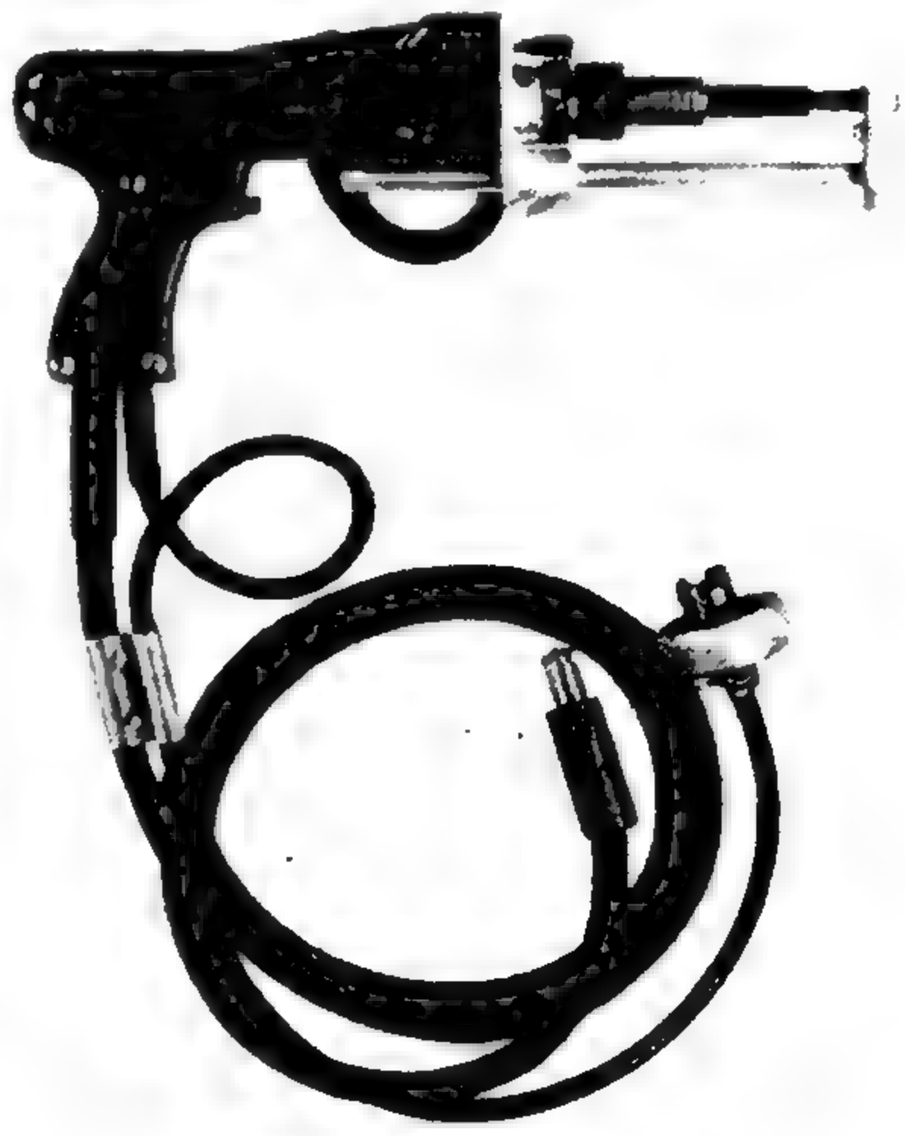


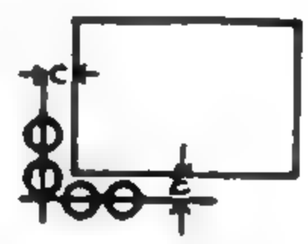
Fig. 2.—Portable Stud Welding Gun

stud gun resembles a pistol with an enlarged bore. Welding current and control leads enter the gun through the handle which also contains a trigger-actuated control switch. A heavy copper

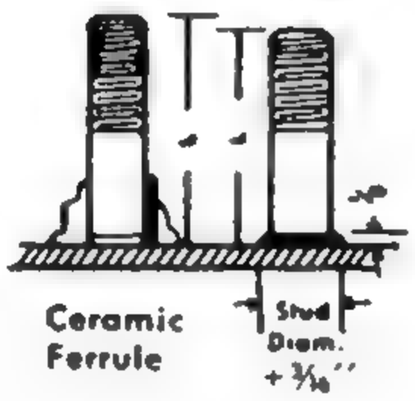
coil is molded into the body of the gun. A solid or stationary core fills one end of this coil while a floating core moves freely in the other end of the coil. The linkage mechanism which causes the stud to be pulled away from the plate to form the arc is attached to the floating core. When the trigger is depressed, welding current flowing through the coil results in a magnetic or solenoid action causing the floating core assembly to move back toward the handle of the gun. The chuck

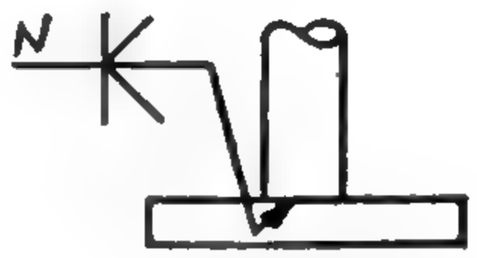
Stud Dia.	MINIMUM STUD CLEARANCES				
	A	B	C	D	E
3/16	5/16	Bend Radius + 5/16	5/16	1/2	Weld Width + 1/4
1/4	5/16	Bend Radius + 5/16	5/16	9/16	Weld Width + 1/4
5/16	3/8	Bend Radius + 3/8	3/8	11/16	Weld Width + 5/16
3/8	3/8	Bend Radius + 3/8	3/8	3/4	Weld Width + 5/16
7/16	13/32	Bend Radius + 13/32	13/32	13/16	Weld Width + 3/8
1/2	15/32	Bend Radius + 15/32	15/32	15/16	Weld Width + 7/16
5/8	9/16	Bend Radius + 9/16	9/16	1 3/32	Weld Width + 1/2
3/4	5/8	Bend Radius + 5/8	5/8	1 7/32	Weld Width + 9/16

Circular Opening



Rectangular Opening





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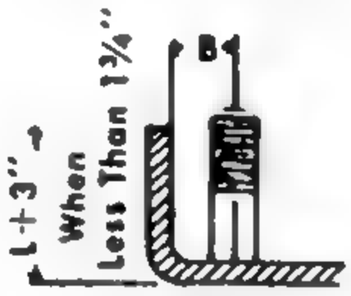
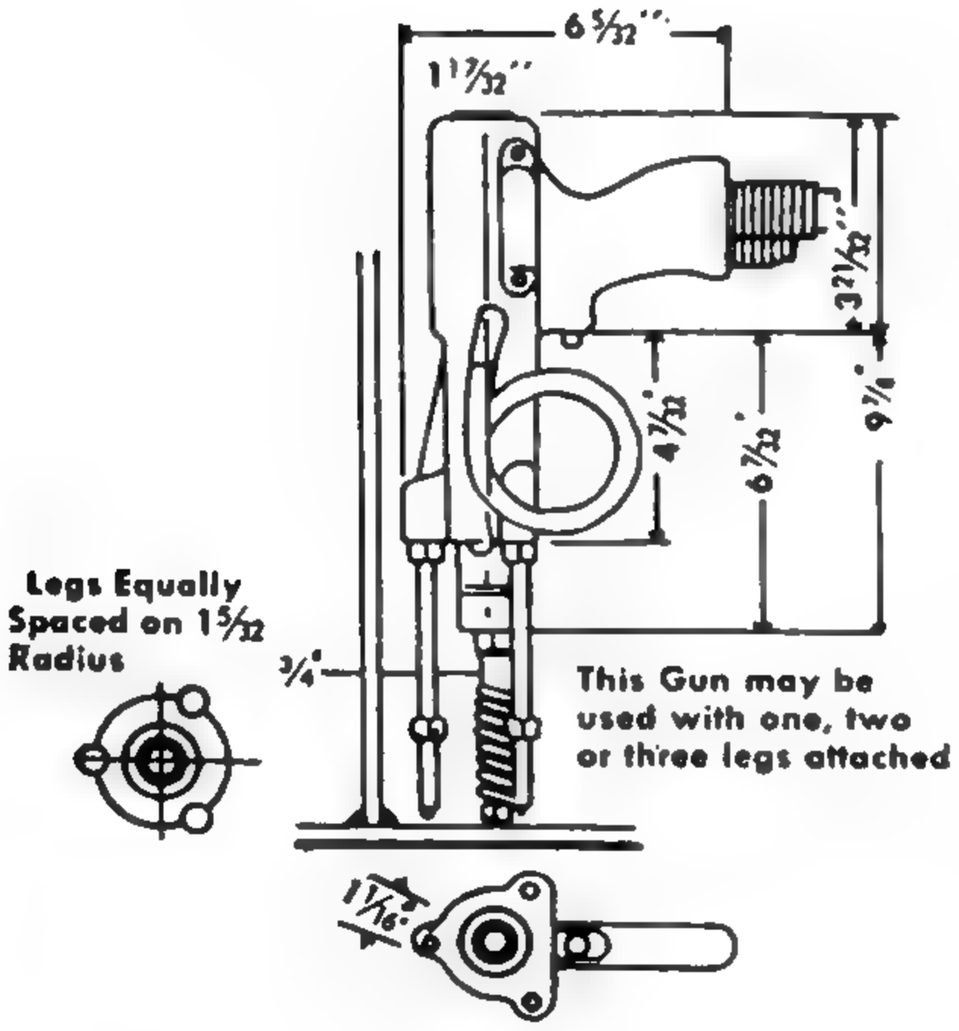
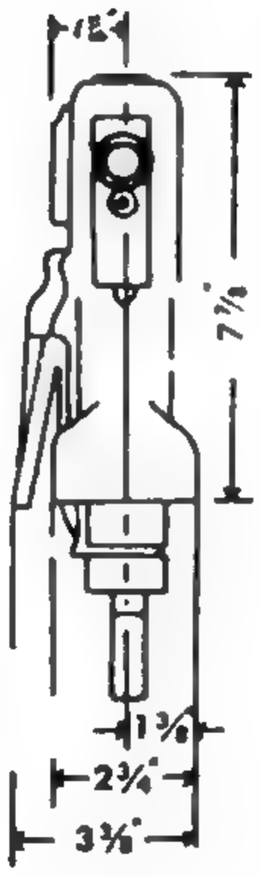






Quick Adjustable Leg

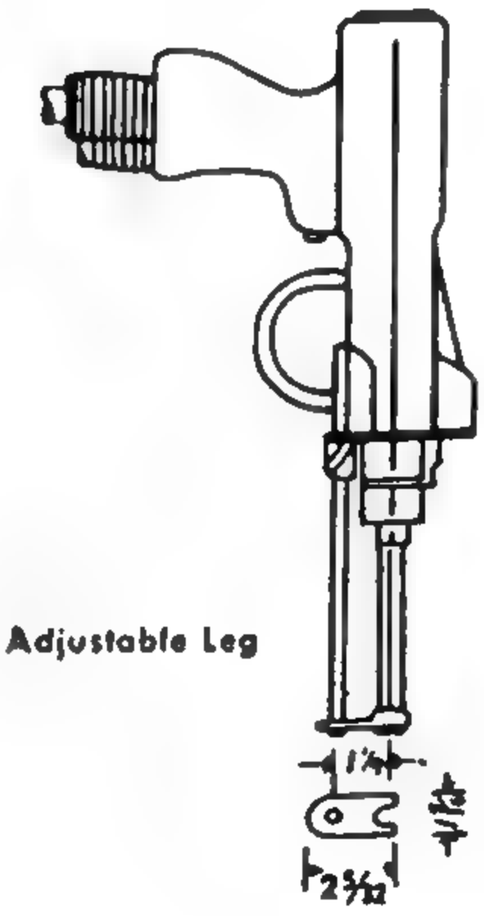


Fig. 3.—Limiting Dimensions of Portable Stud Welding Gun

and stud are thus lifted from the work to draw the arc. At the conclusion of the arc cycle, the current is cut off by the control unit and the main spring within the gun body drives the stud back into the molten pool of metal formed by the arc to complete the weld.

The stud to be welded is held in position by means of a spring chuck which is attached to the lower bearing portion of the stud gun. The chuck size depends upon the size of stud to be welded.

By changing chucks and ferrule holders, it is possible to use the same gun to weld studs varying in diameter from $^1/_8$ to $^3/_4$ inch. Naturally appropriate changes must be made in generator and timer settings. (See Fig. 3 for limiting dimensions of portable gun.)

Production Gun

In principle, the production stud welder is the same as the portable gun. The fundamental difference is that the production gun is mounted on an automatic positioning device, usually air operated and electrically controlled, which permits very careful control of stud location. Tolerances of ±0.005 in. on location and ±0.010 in. in height are possible when the production stud gun is used with adequate locating fixtures to position the workpiece.

The basis of the production unit is the production-model stud gun (see Fig. 4). From one to six or more stud guns may be used in any one production unit depending upon the nature of the job being done and the production rate required.

In a typical production unit the operator loads the studs, ferrules and workpiece and presses the starting button. The gun (or guns) is automatically positioned, the weld is made, and the gun is retracted to the preweld position without further attention from the operator.

For applications where production requirements are extremely exacting, more elaborate units with automatic loading and ejection of workpieces and semiautomatic loading of studs and ferrules have been devised. (See Fig. 5 for limiting dimensions.)

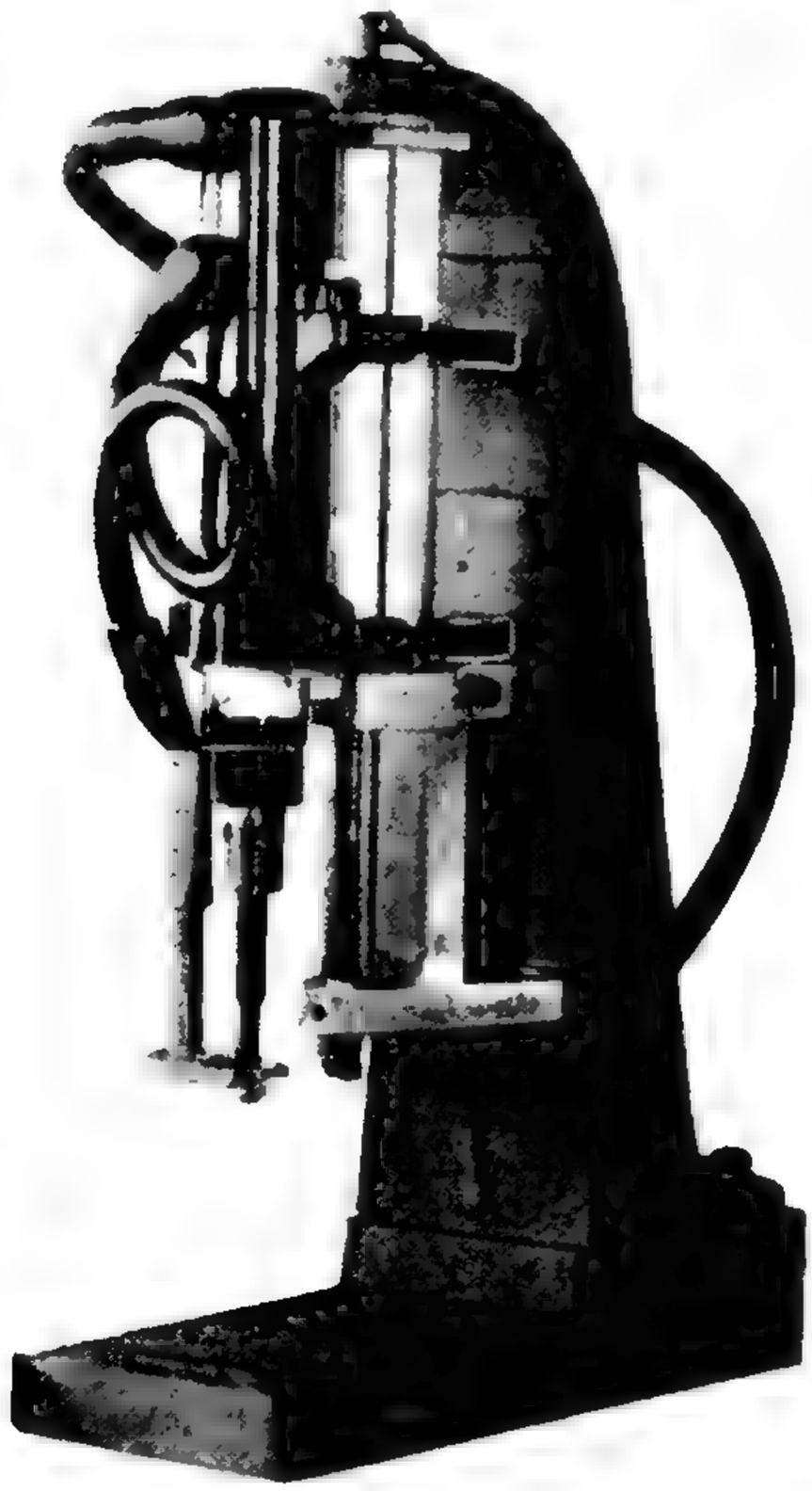


Fig. 4.—Production Stud Welding Unit

Other Equipment

Control Unit.—The control unit consists fundamentally of a high-speed welding contactor and a timing device or devices along with suitable relays to permit the proper wiring of the control circuit. The timing unit is graduated in terms of cycles (60 cycles per second) and is easily adjustable. Once set, the control unit maintains the proper time interval for the size stud being welded. The time interval may vary from 3 to 45 cycles ($^1/_{20}$ to $^3/_4$ sec.) for $^1/_8$- to $^3/_4$-in. diam. studs.

Generators.—The stud welder may be operated with any NEMA rated 300, 400 or 600 amp. d.c. welding generator. (see Chapter 8). The size of machine necessary is dictated entirely by the size of the stud to be welded and the conditions under which the welding must be done. Normally a 300-amp. rated machine with a nominal amount of welding cable (2/0 or larger) will weld a $^3/_8$-in. stud without difficulty. For larger studs up to $^1/_2$ in. in diam., a 400-amp. rated machine is recommended. Where excessive cable lengths must be used, where bad magnetic arc-blow conditions exist, or where the incoming a.c. power condition is questionable, a 600-amp. machine is recommended

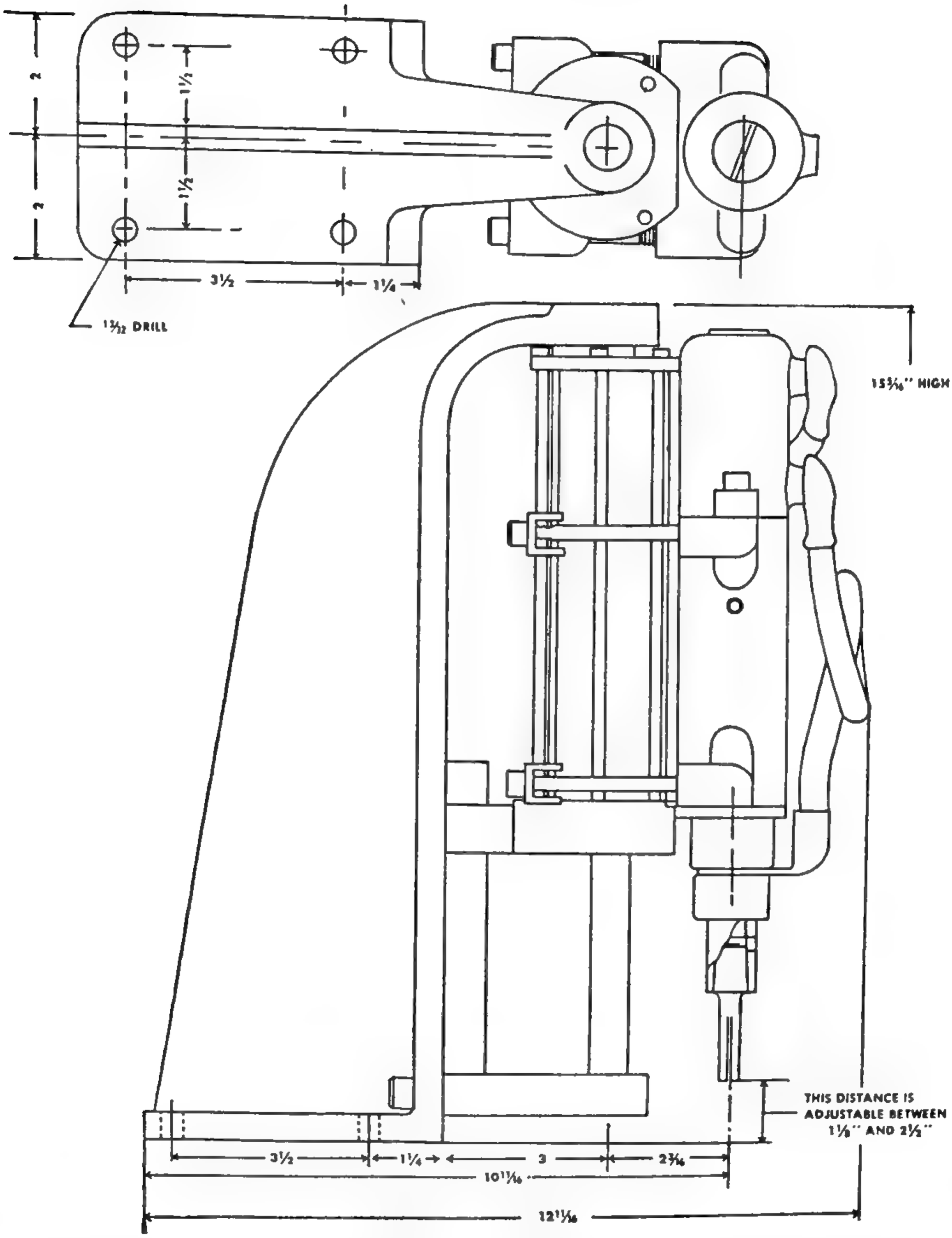


Fig. 5.—Limiting Dimensions of Production Stud Welding Gun

for $^1/_2$-in. diam. studs. (See Fig. 6 for Stud Welder Connection Diagram). The stud-welding gun is connected to the negative pole through the control unit. Straight polarity is always used.

For the welding of $^5/_8$ and $^3/_4$-in. diam. studs it is usual practice to parallel two 400-amp. machines and three 400-amp. machines, respectively.

The stud welder may be operated with portable, engine-driven equipment provided the idler arrangement is by-passed and the generator allowed to operate at constant speed.

Extensive investigation into the problem of stud-welding generators has indicated that the type of d.c. welding machine which reaches peak output in a maximum of 1 to 2 cycles and is able to maintain this maximum output over the entire

welding cycle, is the most satisfactory for use with the stud welder. However, many different d.c. generators which do not have all of the above characteristics are used successfully for certain stud sizes by making proper current, voltage and timer adjustments.

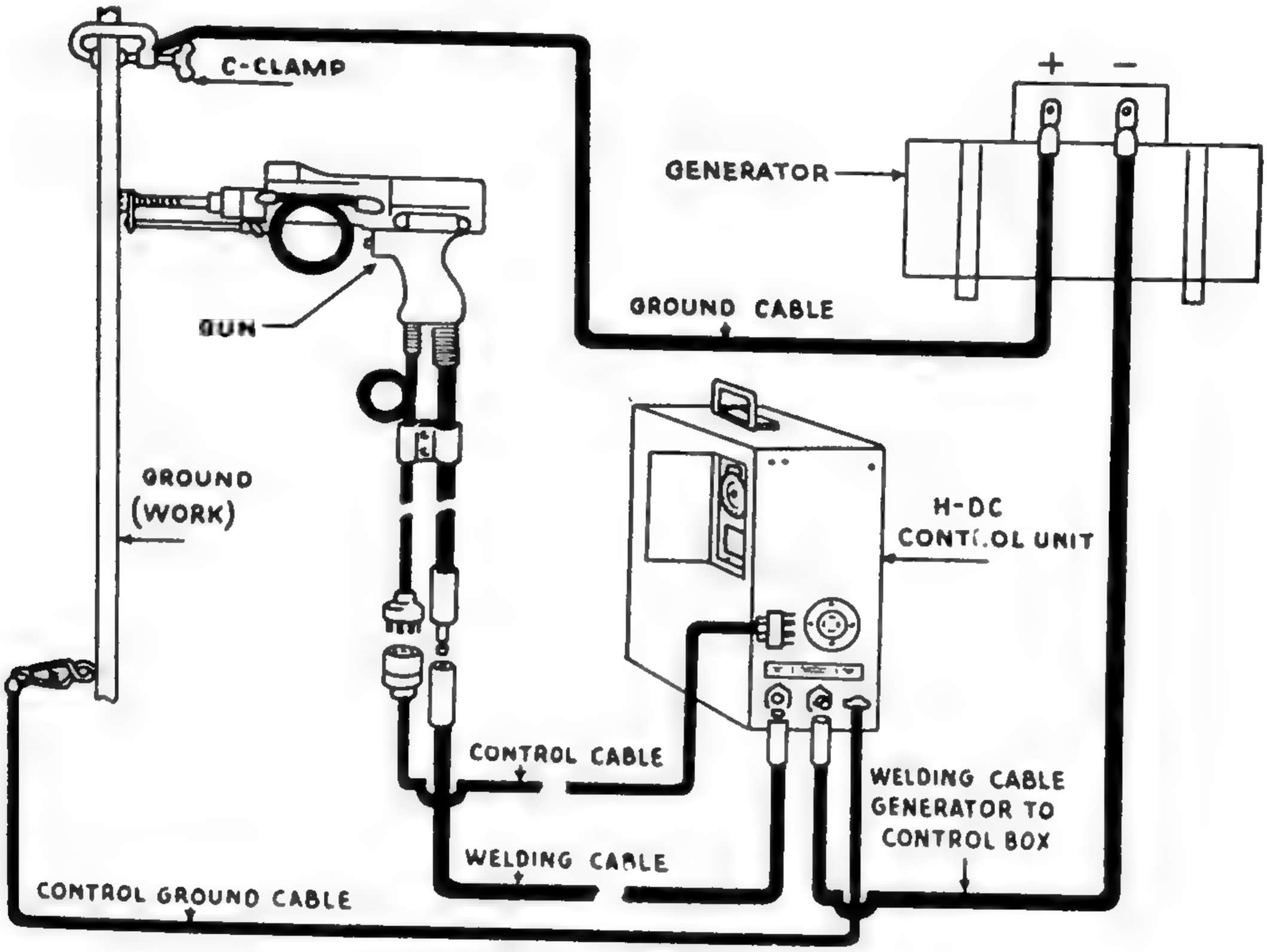


Fig. 6.—Stud Welder Connection Diagram

Studs

The welding end of all-position studs is recessed to contain a quantity of welding flux which is sealed within or permanently affixed to the end of the stud.

This flux acts as an arc stabilizer and deoxidizing agent. The fluxing action combines with the shielding effect of the ferrule to protect the molten metal from oxidation during the melting period. The resultant weld is clean and dense across the full base of the stud. Fusion of the entire base of the stud to the plate makes it possible to develop mechanical properties consistent with the size and type of stud used.

Standard stud material is AISI C-1020 or C-1015. Specifications require a tensile strength of 65,000 to 85,000 psi., yield point 50,000 to 70,000 psi., 20% min. elongation and 55% min. reduction of area. An extensive investigation into the mechanical properties of studs has shown that these values may be taken as characteristic of the stud-welded assembly. For design purposes it is suggested that the smallest cross-sectional area of the stud be used for load determination. Naturally, the usual safety factors should be considered. (See Tables 2 and 3.)

The data in Table 2 are taken from results of a large number of tests made in order to determine the desired specification limits on stud material and each value is an average of several tests. This summary is presented in order to assist in engineering assemblies for stud welding and to show specifically:

1. The strength to be expected in stud-welded assemblies.
2. That failure does not occur in weld.
3. That stud welding does not lower strength of stud by annealing or softening stud near weld, even in highly cold-worked studs.

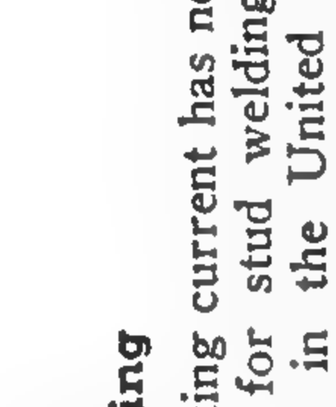
At the present time it is possible to obtain almost any size or shape of stud provided it can be flux-loaded, comes

within the capacity of available welding machines, and a ferrule can be made to go around the stud. A full range of standard stud sizes from 6-32 screws to 3/4 in. in diam., from 3/8 to 9 in. in length, both male and female, tapped or blank are being welded. It is also currently possible to obtain eye-bolt, J-bolt, rectangular and square studs, as well as punched, slotted, grooved, bent and pointed studs. In short, almost any type of fastener, which can be welded on one end, can be stud welded. (See Fig. 7 and Table 4 for typical examples.)

Ferrules.—An individual porcelain ferrule is used with each stud. The ferrule is placed over the end of the stud and held in place by suitable spring, tube leg assembly, or ferrule finger assembly as the particular job may require. The ferrule is a most vital part of the stud welding operation, performing several important functions, as follows:

1. Concentrates the heat of the arc in the weld area during the weld period.
2. Reduces oxidation of the molten metal during the arcing period, by restricting the access of air to the weld area.
3. Confines the molten metal to the weld area.
4. Prevents charring of material through which stud is being welded and consequent contamination of the weld metal.
5. Protects the eyes of the operator from the arc, avoiding the need for the customary welding hood. (Safety glasses are recommended.)

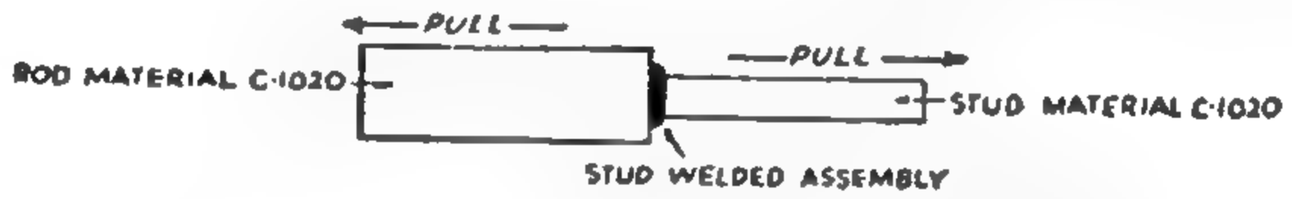
The construction of a standard ferrule is shown in the accompanying sketch, with H and D designating the height and diameter respectively.

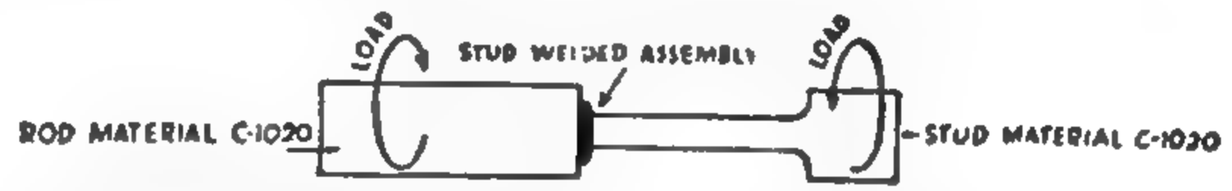


A.C. Stud Welding

As yet, alternating current has not been used very much for stud welding on a commercial basis in the United States. However, a considerable amount of experimental work has been done on this

Table 2—Mechanical Properties of Stud-Welded Joints





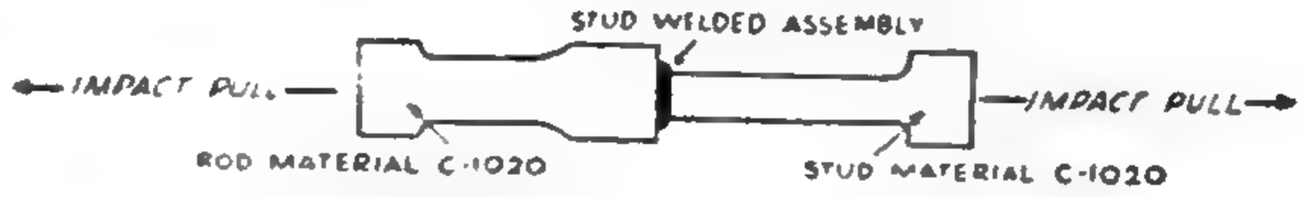
Type Stud	Loading	3/4-In. Diam. Yield Load	3/4-In. Diam. Load at Fracture	5/8-In. Diam. Yield Load	5/8-In. Diam. Load at Fracture	1/2-In. Diam. Yield Load	1/2-In. Diam. Load at Fracture	3/8-In. Diam. Yield Load	3/8-In. Diam. Load at Fracture	1/4-In. Diam. Yield Load	1/4-In. Diam. Load at Fracture
Blank stud	Tension, lb.	27,000	33,000	18,400	23,000	11,800	14,700	6,700	8,300	2,900	3,700
No thread, full diameter	Torsion, in.-lb.	...	5,800	...	3,300	...	1,980	...	840	...	250
Blank stud	Tension, lb.	...	32,400	...	22,400	...	14,000	...	7,800	...	2,700
No thread, 1/2 reduced base	Torsion, in.-lb.	...	5,180	...	3,180	...	1,560	...	740	...	155
Blank stud	Tension, lb.	...	25,400	...	17,900	...	11,300	...	4,500	...	1,250
No thread, full reduced base	Torsion, in.-lb.	...	3,200	...	1,880	...	1,200	...	310	...	50
Threaded stud[a]	Tension, lb.	...	30,600	...	20,200	...	13,200	...	5,200	...	3,300
U.S. std. coarse	Torsion, in.-lb.	...	4,100	...	2,400	...	1,400	...	590	...	170

[a] Tests on threaded studs with dry threads. If threads are oiled or greased, torque results will be 5 to 20% lower, depending on type of oil or grease used, due to less thread friction or more leverage by principle of wedge or inclined plane (Spiral Screw Thread).

1/2 Reduced Base Stud—Weld Base Diameter Reduced 1/16 in.; e.g., 3/8-in. RB Stud Weld Base 5/16 in.

Full Reduced Base Stud—Weld Base Diameter Reduced 1/8 in.; e.g., 1/2-in. FRB Stud Weld Base 3/8 in.

Table 3—Impact Tension Test Data



Diameter, In.	Threaded	Stud Welded[a]
	Energy to Rupture, Ft.-Lb.	
1/4	14.5	72.5
3/8	47.7	219.0
	Break occurred In threads	In stud

[a] Unthreaded specimens. Test designed to test weld section.

Material Used in Test

AISI C-1020, Cold Drawn

Tensile Strength	75,000 psi.
Yield Strength	60,000 psi.
Elong. in 2 in.	24%
Red. of Area	58%

Stud Specification

AISI C-1015 or C-1020, Cold Drawn

Tensile Strength	65,000 to 85,000 psi.
Yield Strength	50,000 to 70,000 psi.
Elong. in 2 in.	20% Min.
Red. of Area	55% Min.
Hardness	Rockwell B-70 to 85

problem as part of the development program on a.c. welding in general.

The principal advantage of the use of alternating current would seem to be the reduction of arc blow and the possibility of obtaining a single welding transformer of any required size to handle any particular size stud. This single machine as a source of power would show to best advantage in those stud welding applications where 6/8- and 3/4-in. diam. studs are being welded in large quantities over a small work area. An ideal example of this would be in the fabrication of Diesel locomotives, where large studs predominate and it is necessary, with d.c. equipment, to connect two or three welding machines in parallel to obtain the necessary power.

There are certain disadvantages in the use of alternating current which must be considered and overcome before a.c. stud welding becomes completely practical.

Reactance.—Variation and loss of power due to variation in reactance in the welding cable circuit presents a definite prob-

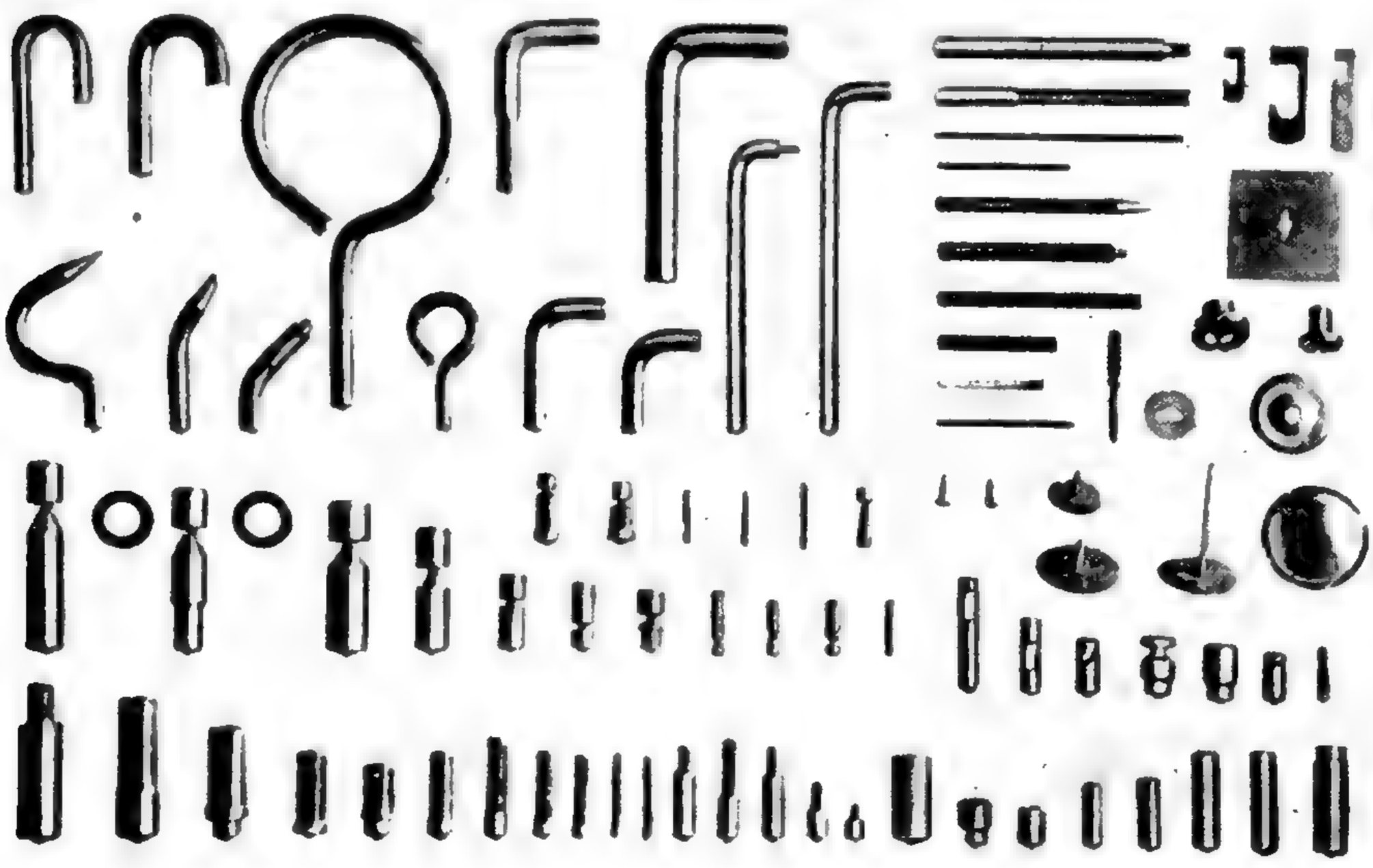


Fig. 7.—Commonly Used Studs and Fastening Devices

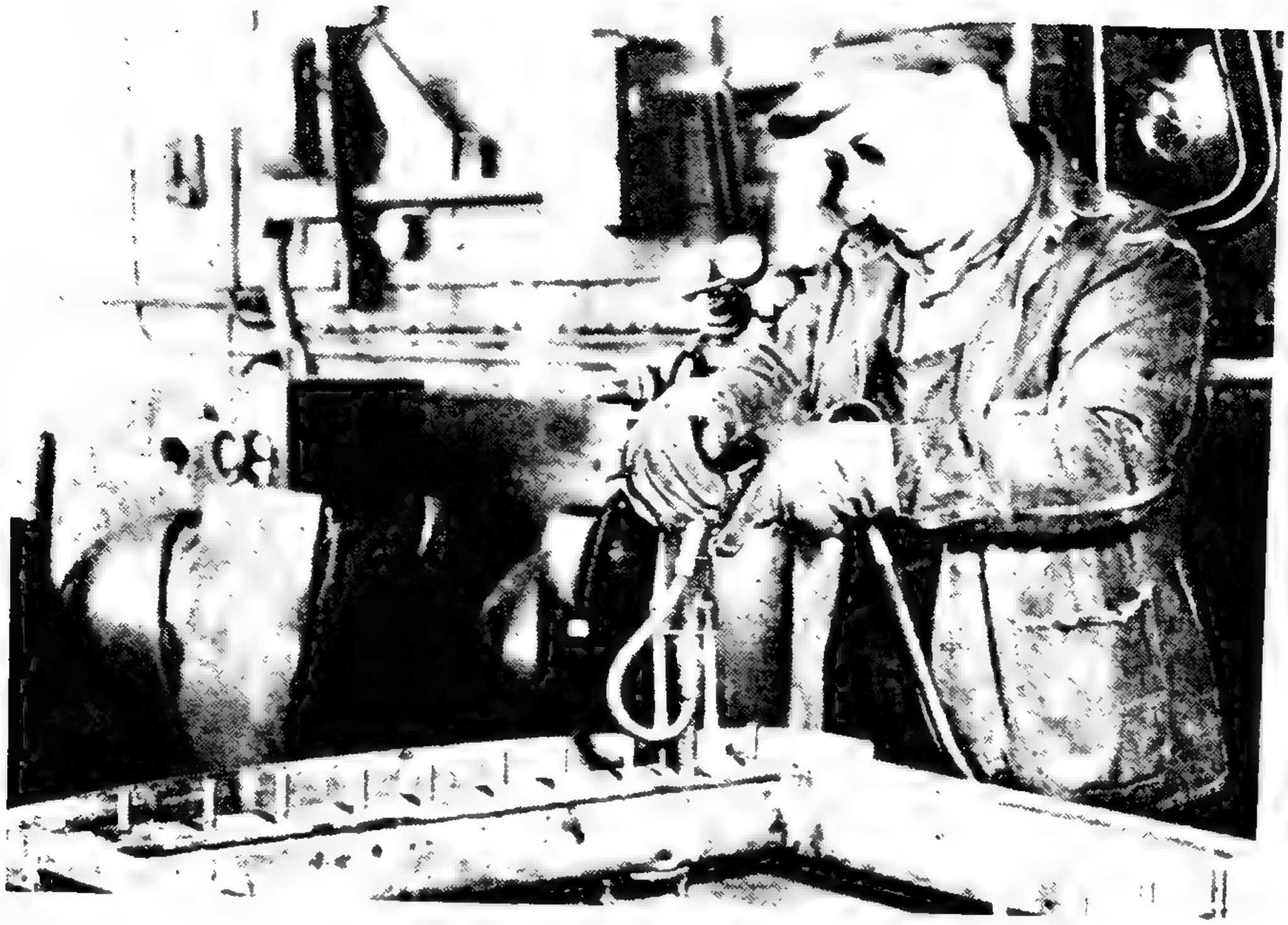


Fig. 8.—Location of Studs by Center Punch Mark on Work

lem. This factor throws a severe limitation on the length of cable permissible, particularly where larger diameter studs are being used.

Several a.c. units have been made and operated in England over the past several years. One is rated at 35 kva. and is recommended for welding up to 1/2-in. diam. studs with a maximum total cable length of 150 feet. Another unit developed in England uses rectified alternating current for welding 5/8-in. diam. studs; the maximum capacity is 180 kva. The procedure with this equipment is to step down line voltage to 100 volts, pass it through a current regulator, and then through a set of oil-immersed ignitron tubes for rectification. The welding principles are the same as previously described except that the arc is established by fusing a small projection on the weld end of the stud instead of using a solenoid.

Locating Devices

The procedure used to locate studs depends entirely upon the intended use of the stud and the accuracy which must be maintained. Where extreme accuracy is required special locating fixtures and the production type stud welder are used. The extent of tooling as a rule will be a function of the production rate as well as the total production. In nearly all cases locating devices would come under the heading of special equipment tooled for the individual job.

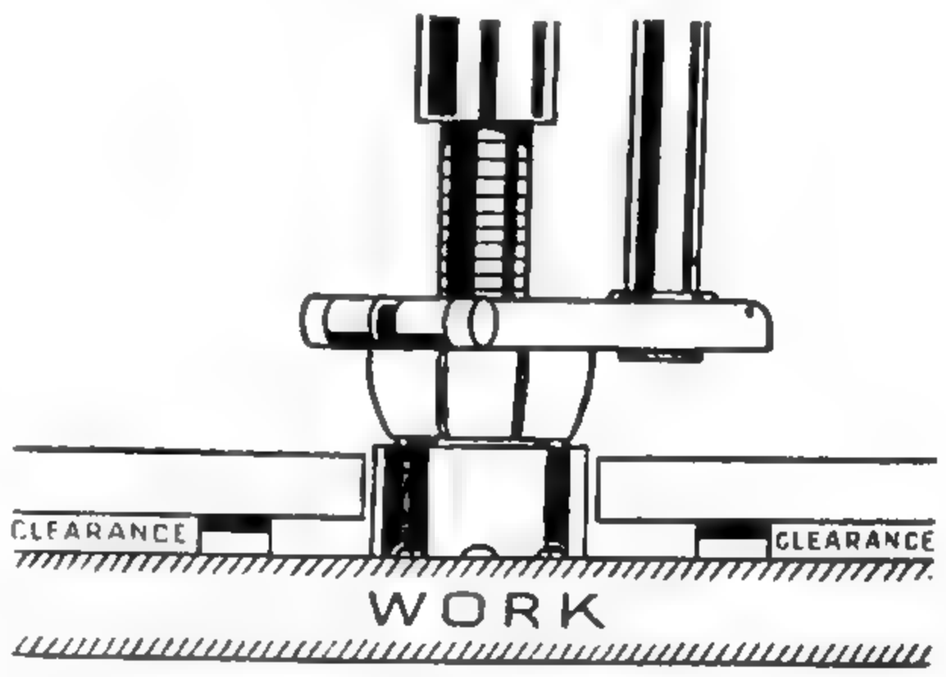
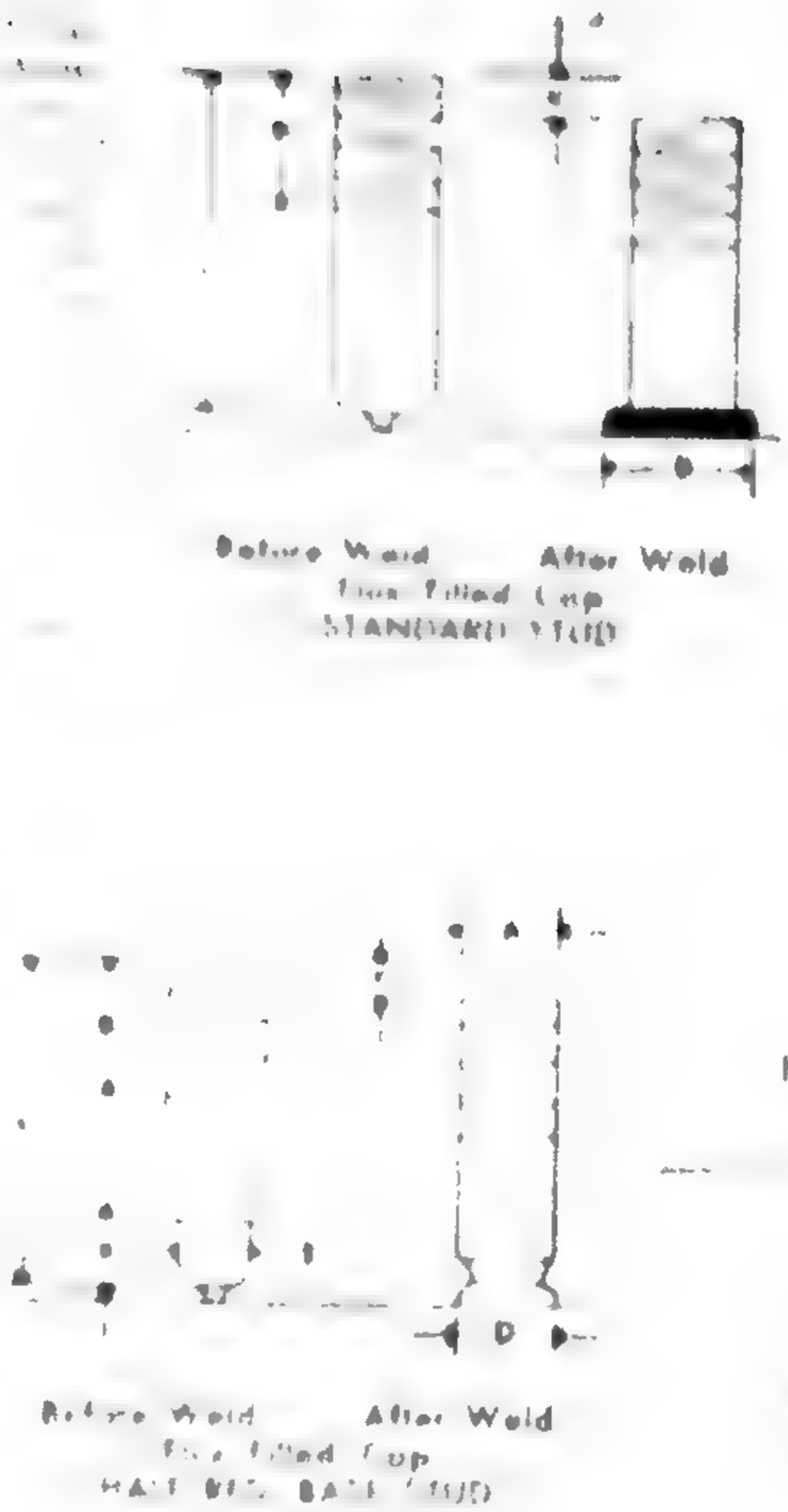


Fig. 9.—Location of Studs by Template (Note Clearance Between Template and Work)

The portable stud-welding gun is by far the most commonly used. It is generally used in those instances where it is impractical to place the part being welded in a locating fixture. Several methods and procedures have been worked out for positioning the stud under these circumstances. The procedures are noted in order of increasing accuracy to meet decreasing tolerances.


Before Weld
After Weld
Approx Size Ferrule

Center Punch Layout Method.—The part to be stud welded is laid out and the stud locations (center) are center punched. (See Fig. 8). The point of each stud is placed in the punch mark prior to welding and in general positions the welding gun. After welding, if care is used, the stud will be reasonably close to the required position. Normal tolerances are $\pm^1/_{32}$ inch.

Template Methods.—Where production is reasonably uniform a simple template is made to locate studs by locating the ferrule. (See Figs. 9 and 10.) The size of hole for ferrule location is usually the maximum ferrule diameter ±0.015 inch. By this means tolerances of $\pm^1/_{64}$ in. may be met. Good design calls for clearance under the template ($^1/_{16}$ in.) to permit proper venting of gases evolved during welding. Special adapters are available which simplify the problem of keeping the stud perpendicular to the welding surface. (See Fig. 11*a*.) Tables 4 and 5 give stud dimensions and welding data.

In order to obtain extreme accuracy several template modifications are being used where the legs of the gun are used to locate the stud indirectly. In one procedure (Fig. 11*b*) the gun is modified slightly to permit positioning of the tripod legs in order that the chuck, the stud and the legs of the gun may be kept concentric. In another case (Fig. 11*c*) the template is prepared by drilling a clearance hole where the stud is to be located. (See also Fig. 12.) Around the hole, and concentric with it, a groove is cut

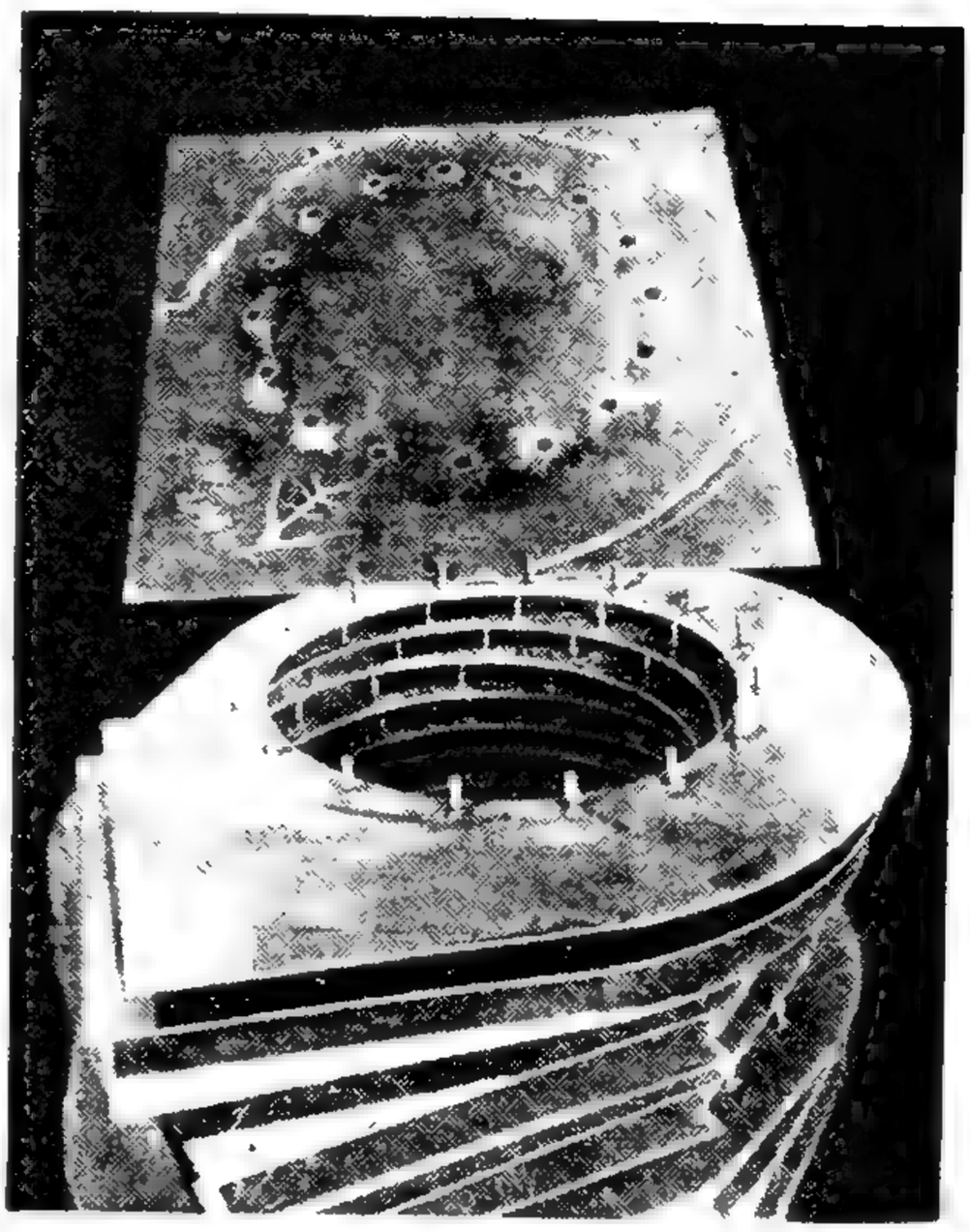
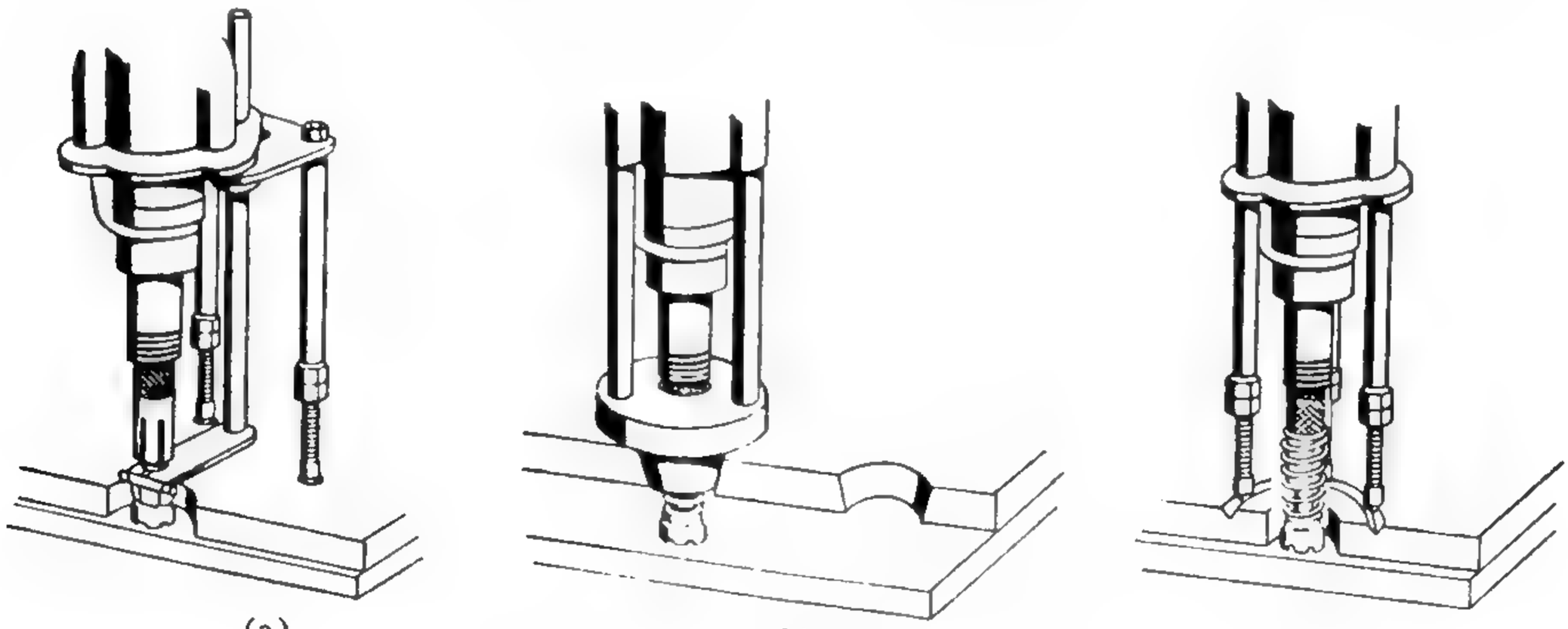


Fig. 10.—Location of Studs by Template on Air Blower

with a fly cutter. The three-pointed legs are placed in the groove and thus automatically place the stud in the center of the hole drilled in the template. It is important that the legs and chuck be checked for concentricity when a chuck is changed. The cone-shaped adapter shown in Fig. 11*b* has also been used to very good advantage. Clearance must be left in the adapter holes to permit alignment of the cone adapter with the chuck and stud.

Accuracies of ±0.010 in. have been



(a) (b) (c)

Fig. 11.—Location of Studs by Template

(*a*) Use of template adapter to give tripod suspension to assure alignment of stud. Stud located by locating pointed legs.
(*b*) Use of locating special cone adapter on the leg supports.
(*c*) Use of locating leg supports on gun.

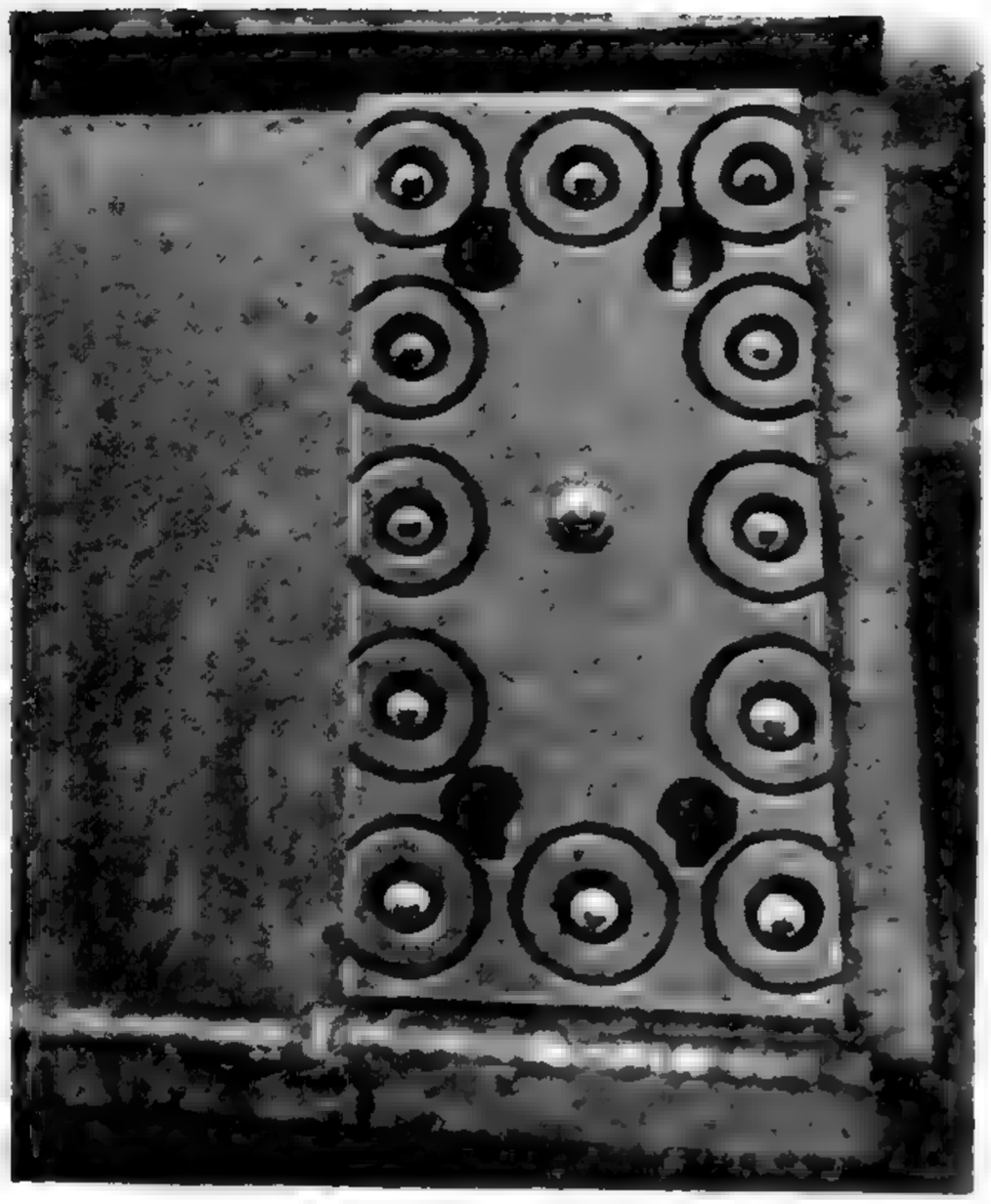


Fig. 12.—Application of Template Method Illustrated in Fig. 11c to Secure CamShaft Covers on Diesel Locomotive Engine

maintained with these methods. It should also be noted that the hole in the template is considerably larger than the ferrule used and venting is thereby

COMMON APPLICATIONS

General

Stud welding is above all else a fastening method and as such has been accepted by practically all metal-working industries. The type of fastener to be used will vary according to the problem at hand.

The most advantageous use for end-welded studs depends upon the method of fabrication with which a plant is most familiar and the method of routing the material through a plant. Generally, if there are shot-blasting or pickling operations to be applied, it would be most desirable to put the studs on the parts just before final assembly as this would minimize damage due to handling. The application of studs does not interfere with painting operations and no cleaning is necessary subsequent to painting operations. If the parts are relatively small and varied in nature and if there is sufficient production, a station for applying studs can be established before parts are distributed to various assembly sections.

Set-up time becomes a factor in stud welding when the stud diameter and length change. It is necessary to change the chuck of the gun for different diameters and also to change the length of the gun supports for the different lengths of studs. This is a simple matter but, nevertheless, it is advantageous to keep the size and type of studs standardized as much as possible. Undue changing of length or diameters may materially reduce the possibility of effecting economies through use of stud welding.

Specifically stud welding is now being used extensively in the following industrial fields: Shipbuilding, railroads, construction, equipment manufacture, automotive, and boilers.

Shipbuilding

The portable stud welder is used under

Table 5—Stud Welding Conditions

Major Stud Diameter, In.	Type Weld*	Current Setting	Weld Time, Cycles
[illegible]	RB	[illegible]	5
[illegible]	RB	[illegible]	5
[illegible]	RB	[illegible]	8
[illegible]	RRB	[illegible]	8
[illegible]	RB	[illegible]	8
[illegible]	RRB	[illegible]	12
[illegible]	RB	[illegible]	9
[illegible]	RRB	[illegible]	13
[illegible]	RB	[illegible]	12
[illegible]	RRB	Wide open	15
[illegible]	RRB	[illegible]	18
[illegible]	RRB	2 400 amp (two paralleled, 1 200 amp each machine)	20
[illegible]	RRB	2 400 amp (two paralleled, 1 200 amp each machine)	25

NOTE—All above settings are based on using 100 feet of 2/0 welding cable.
*RB—welding diameter is [illegible] less than major stud diameter; RRB—welding diameter is [illegible] less than major stud diameter

approval of the Army, Navy and Maritime Commission for securing wood decking, insulation of all types, electrical wireways and control panels, furniture, magnesite flooring, sheet metal covering, piping, gage lines and other applications where practical. (See Chapter 52.)

Railroads

The stud-welding process is now being used by practically all car and locomotive-building shops for a wide variety of applications, including:

Securing wood liners and furring strips, placard holders, etc., in steel box cars.
Securing steel liners in automobile-part cars.
Cab linings for steam locomotives.
Securing wire, cables and conduit.
Cover plates on Diesel engines.
Braking resistors on Diesel engines.
Side sheets on Diesel engines.
Insulation on tank cars and box cars.
Hatch cover studs on refrigerator cars.
(See Chapter 53 for full details.)

Building Construction

The portability of the stud welder makes it an ideal tool for the construction industry. The process has been listed by Underwriters' Laboratories for attaching sprinkler systems. Other applications include the attachment of plumbing, heating ducts, insulation, roofing and siding of all types, and reinforcing rods for concrete and gunite.

General Industrial Equipment

Industrial manufacturers have found stud welding very useful for the placing of studs which were formerly drilled and tapped. The increased production obtained and the possibility of redesign with elimination of heavy bosses formerly required to obtain tap depth has effected remarkable economies in many instances. (See Fig. 13 for illustration of design possibilities.)

Automotive Applications

Studs are being used to secure numerous parts and assemblies to automobile frames and bodies. Among them are the following:

Bumpers.
Bumper guards.
Shock absorbers.
Center support brackets on three-piece drive shaft.
Brake and clutch pedals.
Sun visor supports.
Spare tire mounting studs.
Map light mounting studs.
Rub rails on panel trucks.
Wood floors on buses of all types.
Hand rails on busses.
Rope hooks on various types of trucks.
Studded flanges for securing relief and quick opening valves on various types of tank trucks.

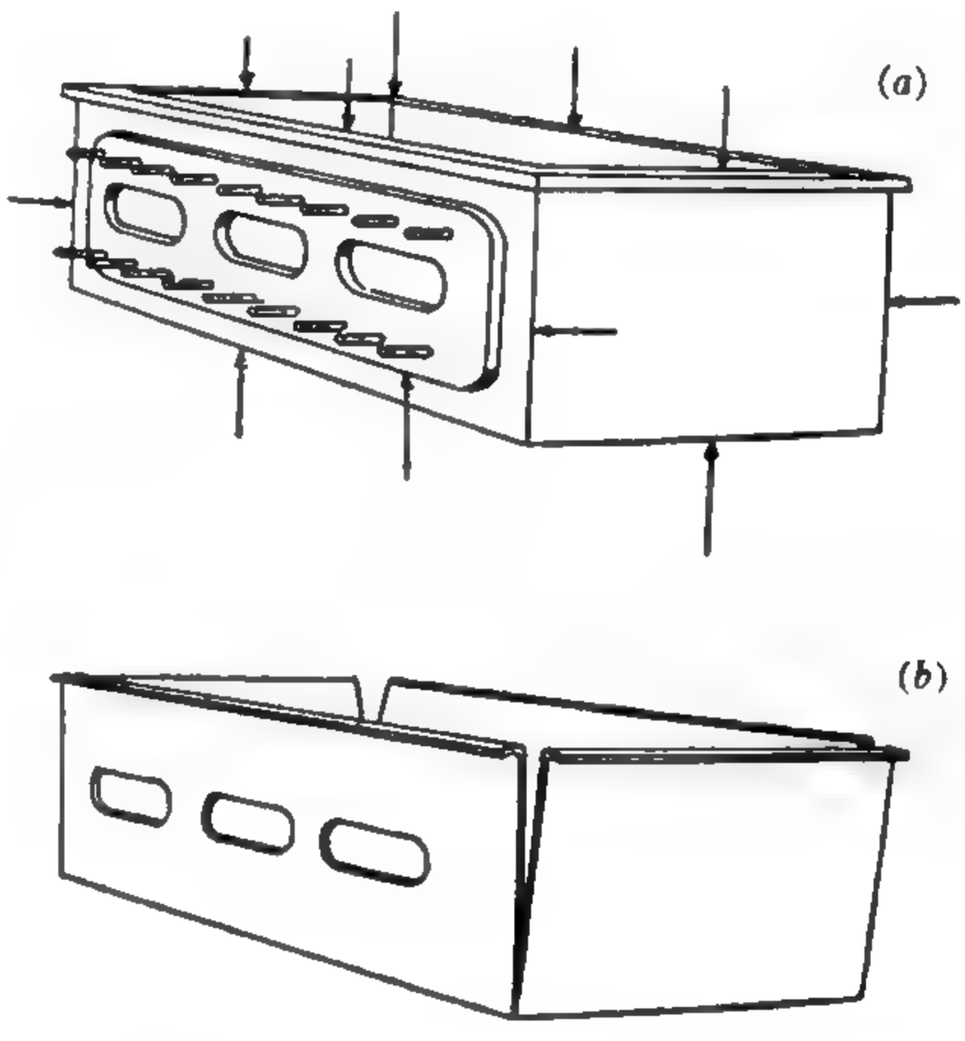


Fig. 13.—Designing for Stud Welding

(*a*) Typical design for underground switch gear prior to stud welding. Note heavy bosses and flanges necessary for tap depth. Arrows indicate welded areas.
(*b*) Welding of flanges eliminated by bending side plate material to form gasketing surface.
(*c*) Stud welded unit complete.

Boilers

Stud welding is approved for use on low-pressure heating boilers built under the ASME Boiler Code for all applications except staybolts. This includes all cover plates, clean-out doors, water-heater coil openings, etc. Staybolts also are being welded on non-code boilers.

Stud welding is approved for use on non-pressure parts on power boilers and unfired pressure vessels built to the ASME Code. (See Chapter 51.)

Other Applications

Studs are commonly used in the manufacture of:

Electrical switch gear of all types.
Metal furniture.
Forged high-alloy turbine blades.
Fans and air-moving equipment.
All forms of furnaces and heat-treating equipment.
Gas pumps, air compressors, hydraulic hoists and many other similar type applications.
Securing rasp bars in combine harvesters.
Securing cover plates and filter elements in commercial oil filters.
Securing cover plates and flanges on all types of oil, gas and electrical transformers.
Securing stainless steel studs to underground junction boxes for telephone cables.
Access doors and clean-out doors on all types of metal degreasing equipment.
Inner shell support members for cold-wall type refrigerated tanks.
Support studs for securing heating elements on mangle-type electric ironers.
Securing all types of insulation, lagging material, etc.

BIBLIOGRAPHY

1 *Electric Arc Stud Welding*, R. C. Single ton. The Welding Journal, December 1947

Stud *Welding in Great Britain*, A. H Reed. The Welding Engineer, January 1948

CHAPTER 15

RESISTANCE WELDING EQUIPMENT*

INTRODUCTION

THE EQUIPMENT required to perform a resistance-welding operation may be very simple and inexpensive, or it may be very complex and costly, depending on the nature and physical proportions of the work, the quality desired and production requirements. A standard piece of equipment has three principal elements:

1. The electrical circuit. This consists of a transformer and a current regulator (tap changer) and a secondary circuit to conduct the welding current to the electrodes.
2. The mechanical system, which holds the work-pieces and applies the required welding force or pressure.
3. The control or timing apparatus. While these controls may sometimes be complicated and control other variables, in the simple machine the control of time only will be considered.

Thus, these three elements of the equipment control the three principal variables in resistance-welding operations: (1) the current, (2) the welding force or pressure and (3) the time. With individual machines, these elements may be considerably complicated and augmented by the use of fixtures, special tooling and handling devices; also by the use of special sequencing controls, voltage and current regulators, etc.

Various means have been devised to reduce the heavy intermittent demands on the power lines required by standard single-phase machines. Stored-energy machines, in which the energy required for each weld may be drawn slowly from the power lines, accumulated within the machine and then discharged for each weld, have been used with considerable success.

Three-phase machines are now being built, in which energy is taken from all three phases of the power line and commutated to a lower frequency, single-phase current.

Capacitors, or condensers, may also be applied to standard single-phase machines to reduce their demand by increasing their power factor.

As far as the weld itself is concerned, it makes practically no difference whether the machine is a stored-energy type, a 3-phase type or whether or not it has power-factor correction; the mechanical operation of the machine may be assumed to be unaffected by the type of electrical operation.

However, with some types of controls, the wave shape of the welding current can be readily controlled, and it is believed that this wave shape does have some effect on the weld.

Throughout this chapter, all data, information and references will apply specifically to standard single-phase machines unless otherwise mentioned. The other types of machines will be considered separately.

This chapter describes only the equipment used in resistance welding. For further information on the processes refer to Chapter 16 for Spot, Seam and Projection Welding, and Chapter 17 for Flash, Upset and Percussion Welding.

TYPES OF SINGLE-SPOT WELDING MACHINES

Rocker-Arm Spot-Welding Machines

The simplest and most commonly used spot-welding machine is the rocker-arm type, so called because of the rocker arm or walking beam movement of the upper arm. This machine is readily adaptable for ordinary spot welding on most weldable metals, where highest quality of work is not of prime importance. It is

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* Prepared by a committee consisting of E. J. Del Vecchio, Swift Electric Welder Co., *Chairman;* L. W. Boelter, Climax Mfg. Co.; G. W. Garman, General Electric Co.; C. B. Stadum, Westinghouse Electric Corp.

generally available in three types of operation: (1) foot, (2) air, and (3) mechanical or motor and cam. It will be shown in this chapter that it is desirable to keep the throat depth of a welding machine as short as possible to make a given weld with the least power demand. Figure 1 (*a*) shows a simple foot-operated rocker-arm machine. This machine, whether foot, air or mechanically operated, has the disadvantage of a reduction of available welding force as well as welding current as the throat depth is increased. On the other hand, the throat depth can be readily changed merely by the substitution of different horns. Some makes of machines have adjustable upper horns and in addition, in some cases, adjustable lower horns.

The rocker-arm machine is well suited for a wide range of work, up to a welding capacity of about two pieces of $^{1}/_{8}$-in. thick steel. Foot-operated machines are best suited for miscellaneous job shop work including many sheet-metal fabrications. Air-operated machines are best suited for production runs, particularly where the runs are not too long and a minimum of set-up time is required. Motor-operated machines are ideal for long production runs, or where air is either at a premium or not available.

Rocker-arm machines are available in throat depths of from 12 to 48 in., and in transformer capacities from 10 to 50 kva.

As may be seen from a comparison of Figs. 1 (*a*), 1 (*b*) and 1 (*c*) the general construction of the machine is the same, regardless of the type of operation.

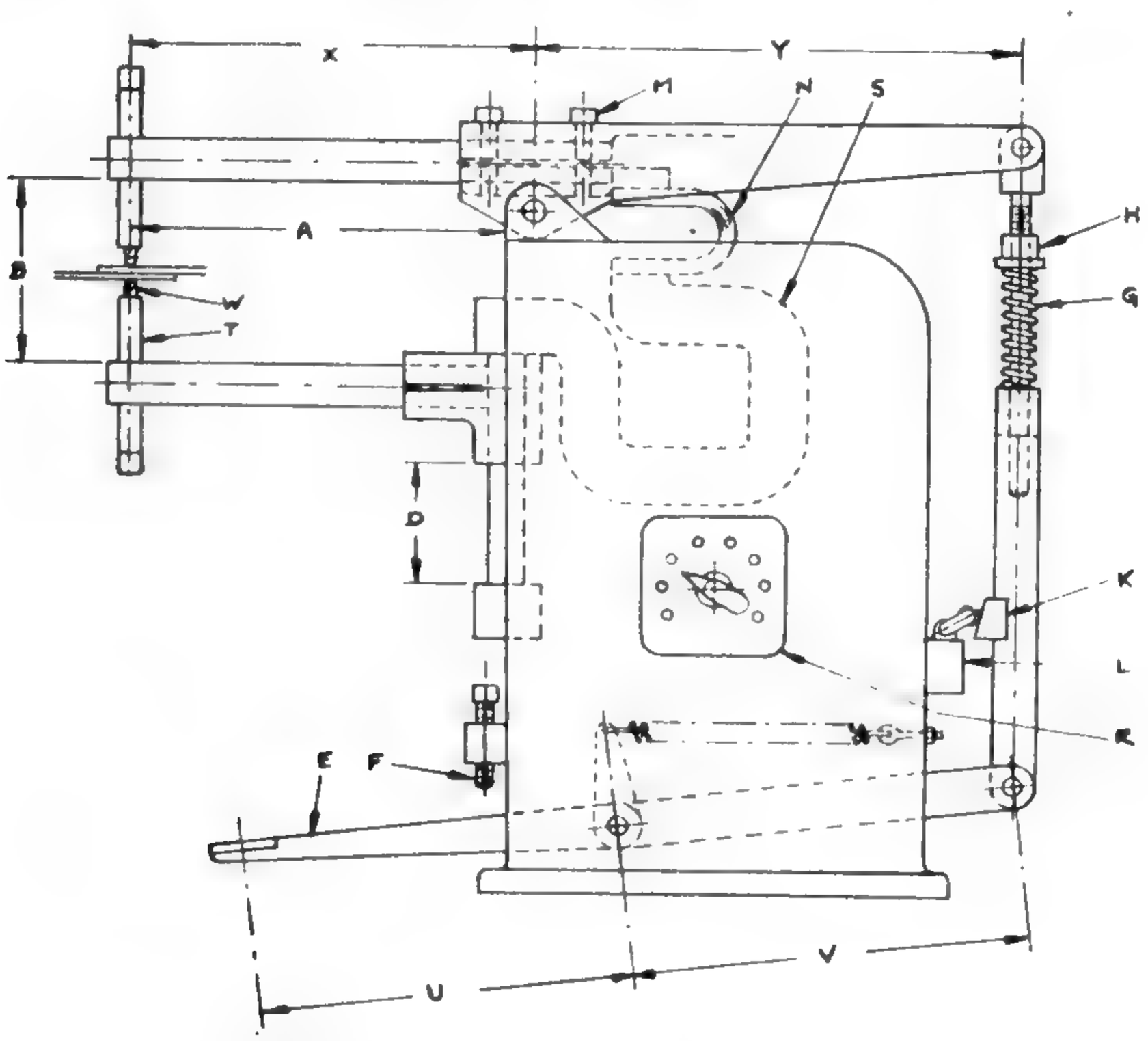


Fig. 1 (*a*).—Standard Foot-Operated Rocker-Arm Spot-Welding Machine

A, Throat depth; *B*, Horn Spacing; *C*, Centerline of horn lever trunnion; *D*, Lower arm vertical adjustment; *E*, foot lever; *F*, Foot lever adjustable stop which regulates amount of electrode opening; *G*, Welding pressure spring; *H*, Welding pressure spring adjustment which regulates amount of welding pressure; *K*, Initiating switch cam or trigger; *L*, Initiating switch; *M*, Horn cap screws; *N*, Secondary flexible bands; *R*, Current regulator; *S*, Transformer secondary; *T*, Water-cooled electrode holders; *W*, Welding points or electrodes.

Electrode Settings.—Since the motion of the upper electrode is in the form of an arc with radius *X*, the electrodes should be set so that the upper electrode is exactly perpendicular to the work when it contacts the work. In this position,

the two arms or horns will be parallel. Any other setting will leave the horns out of parallel, resulting in more or less electrode skidding with consequent unnecessary electrode marking. It is due to this radial motion of the upper electrode that projection welding (except for single projections) is seldom practicable on rocker-arm machines.

Mechanical Principles—Foot-Operated Machines.—The frame of the machine acts as a housing for the transformer and regulator as well as the pedestal upon which are mounted the mechanical elements. On the foot-operated machine these elements consist of two simple levers connected by a spring. From Fig. 1 (*a*), force exerted on the foot lever *E* is transmitted through spring *G* to rocker-arm lever, thence to welding electrode.

Calculation of Welding Force or Pressure.—A compression spring exerts its maximum force when its coils are closed tight. This force is determined by the wire size, coil diameter and pitch. The force exerted when the coils are partially closed will be in proportion to the amount of closure. Thus, if a spring has a free length of 9 in. and a closed length of 8 in. and exerts a force of 1000 lb. at the closed position, it will exert 750 lb. at $8^1/_4$ in., and no force at 9 inches. Forces of closed springs may be obtained from handbooks or spring manufacturers' catalogs. If the force exerted by the spring is 200 lb., then the electrode force is $200 \times Y/X$, (Fig. 1 (*a*)). In actual practice, the spring is often operated fully closed, in which case the electrode force is proportional to the force exerted on the foot pedal. Then electrode force = foot force $\times U/V \times Y/X$. This ratio seldom exceeds 3 to 1, so that an electrode force of 300 lb. requires a foot force of 100 lb., regardless of whether or not a spring is used. This ratio is not affected much by throat depth, for as X is increased, U is also increased. From the above, it may be seen that the limiting factor on a foot-operated machine is the available welding force and the element of fatigue of the operator.

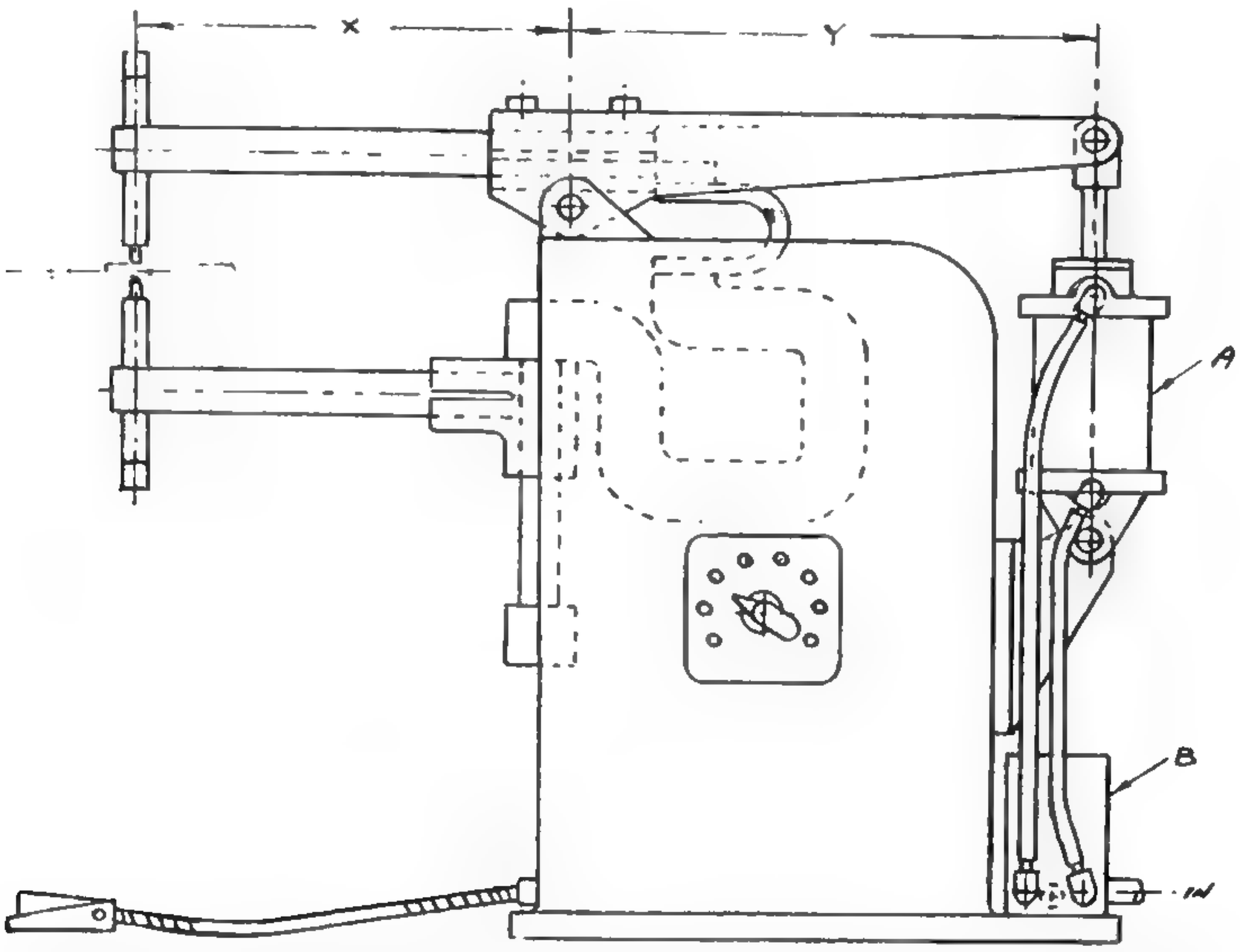


Fig. 1 (*b*).—Standard Air-Operated Rocker-Arm Spot-Welding Machine

A, Double-acting air cylinder; *B*, Four-way valve. This valve may be foot operated, or solenoid operated and controlled by foot switch. Air accessories not shown, but as usually furnished include a lubricator, strainer, pressure-regulating or reducing valve and pressure gage.

Mechanical Principles—Air-Operated Machines.—About the only difference between foot- and air-operated machines is the substitution of an air cylinder for the foot lever and connecting rod. Figure 1 (*b*) illustrates this. The air cylinder

may be mounted as shown in the sketch, or it may be trunnion mounted. The stroke of the cylinder must be proportioned to the required point opening, and its diameter proportioned to the required electrode force and throat depth. For any given cylinder diameter and stroke, the welding force decreases and point opening increases as the throat depth increases. It is usually sufficient to regulate point opening by adjusting the position of the electrodes in the horns. However, in some cases, it is desirable to use adjustable stroke or adjustable-retractable stroke cylinders.

should not be used because of probable erratic and inconsistent results.

Mechanical Principles—Motor-Operated Machines.—Motor-operated machines are similar in principle to foot-operated machines with the substitution of a power-driven cam to operate the rocker arm in place of the foot lever and connecting rod. There are, however, a few important considerations: the machine can never be operated with the spring completely closed; the point opening is determined by the throw of the welding cam and throat depth and no adjustment can be made by positioning the electrodes.

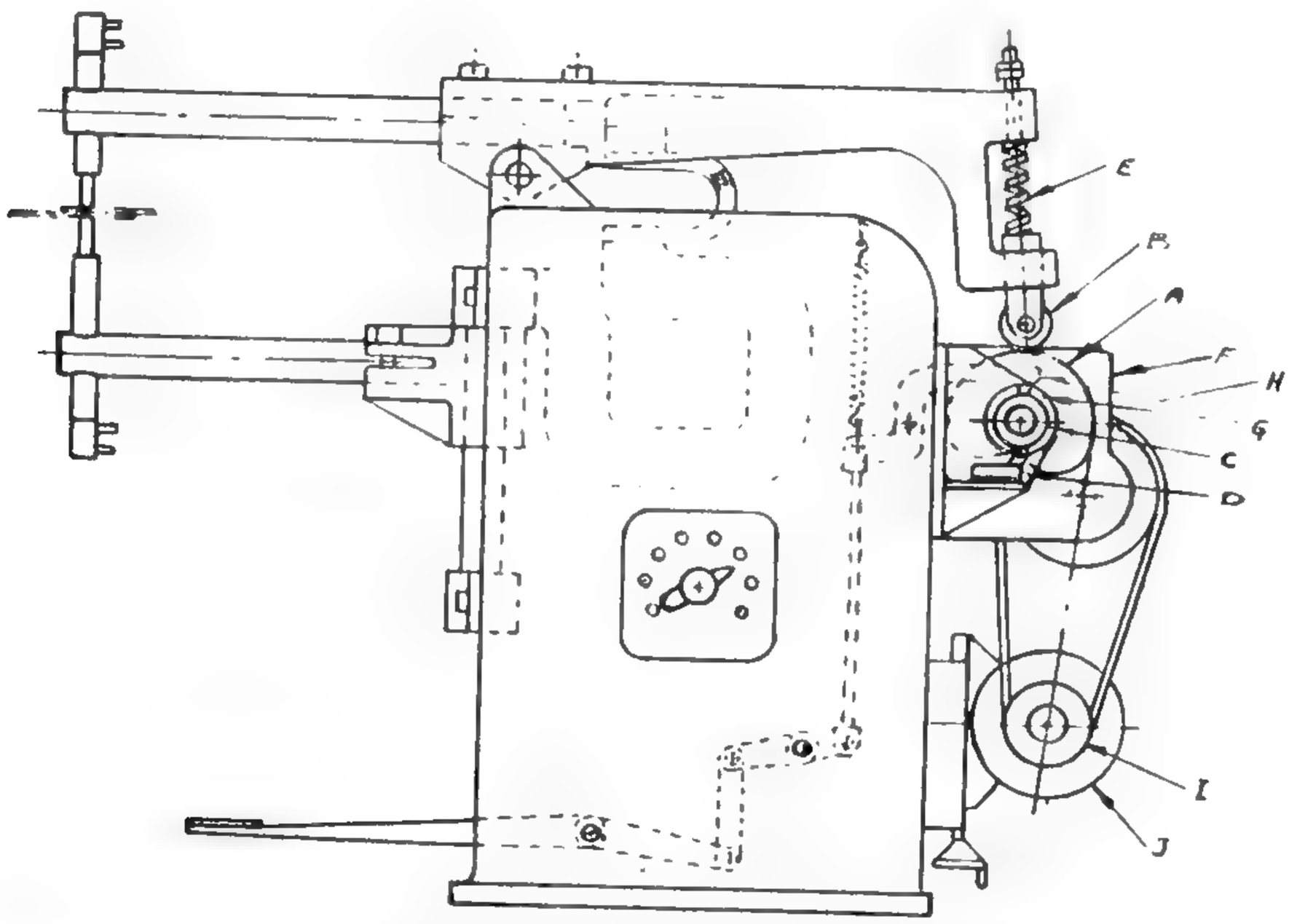


Fig. 1 (c).—Motor-Operated Rocker-Arm Spot-Welding Machine

A, Welding cam; *B*, Cam follower; *C*, Timing cams; *D*, Initiating switch; *E*, Welding spring; *F*, Gear reducer; *G*, Clutch; *H*, Foot-operated clutch trip; *I*, Variable speed drive; *J*, Motor.

Calculation of Welding Force.—The force exerted on a piston is equal to the product of its area (sq. in.) and the air pressure (psi.). Most industrial air systems are operated at 80 psi. pressure, and cylinder diameters are determined on this basis. Then, from Fig. 1 (*b*), electrode force equals piston force $\times$ Y/X. The welding force is in direct proportion to the air pressure and is controlled by the pressure regulator. These calculations do not take into account packing friction, but this is negligible if the cylinder is well lubricated. Air pressures below 20 psi.

If the machine is properly set up, little actual power is required, for it is only necessary for the cam to compress the spring approximately $^{3}/_{16}$ in. for each weld.

The cam shaft usually carries fan-type timing cams which, through a limit switch can operate the welding contactor direct with an accuracy as good as any non-synchronous timer. However, every time the speed is changed, the timing is changed, and it is often more desirable to interpose a simple timer and use the limit switch to initiate the timer (see Fig. 1 (*c*)).

Calculation of Welding Force.—Welding force can be calculated from spring compression and ratios of leverage involved in the same manner as outlined for foot-operated machines.

Press-Type Spot- and Projection-Welding Machines

For all projection welding, and spot welding of better quality, press-type machines are recommended. A press-type machine is one in which the movable electrode and welding head are moved in a straight line and guided in bearings or ways. These bearings must be of sufficient length and proportions to withstand the offset loads put upon them.

Standard press welding machines are furnished in capacities of 50 to 600 kva. and more, and in throat depths up to 48 inches. (They are also furnished in smaller ratings—particularly bench-type models ranging down to 1 kva. These small models are similar to the larger ones but space does not permit more detailed description.)

Press-welding machines are classified in various ways:

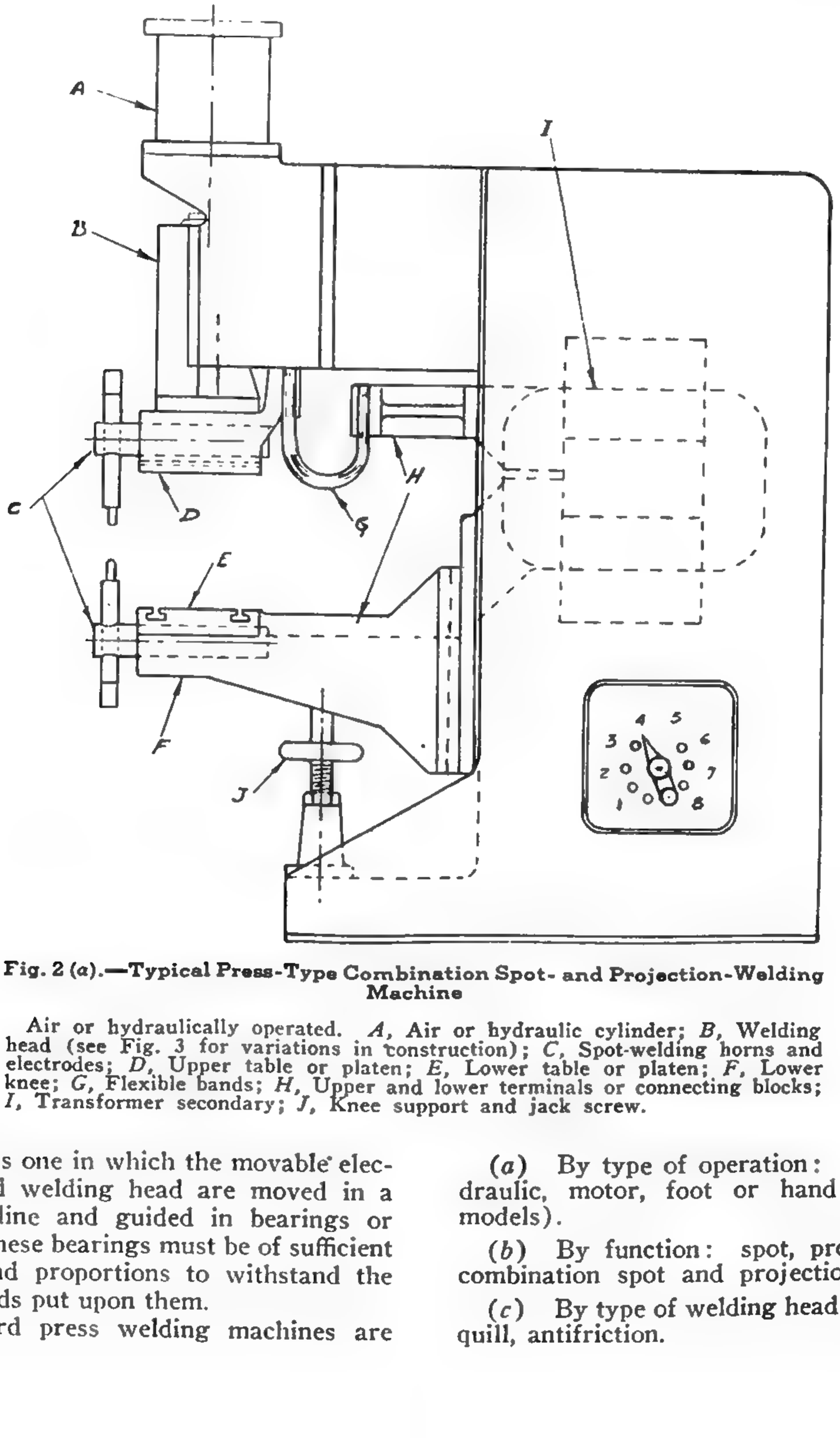


Fig. 2 (*a*).—Typical Press-Type Combination Spot- and Projection-Welding Machine

Air or hydraulically operated. *A*, Air or hydraulic cylinder; *B*, Welding head (see Fig. 3 for variations in construction); *C*, Spot-welding horns and electrodes; *D*, Upper table or platen; *E*, Lower table or platen; *F*, Lower knee; *G*, Flexible bands; *H*, Upper and lower terminals or connecting blocks; *I*, Transformer secondary; *J*, Knee support and jack screw.

(*a*) By type of operation: air, hydraulic, motor, foot or hand (small models).

(*b*) By function: spot, projection, combination spot and projection.

(*c*) By type of welding head: slide, quill, antifriction.

(*d*) By manner of pressure application: direct, toggle.

Some of the above construction variations represent various manufacturer's ideas on the best construction principles. Others are variations which practically all manufacturers furnish to meet various job requirements. It is impossible to set down any rules governing the selection of machine type, but a few general principles may be stated:

(*a*) Motor-operated machines are practically never used above 250 kva., and motor operation is on the decline for all ratings. The main reason for this is the lack of flexibility obtained as compared with air or hydraulic operation.

(*b*) Hydraulic operation is seldom justified below about 200 kva. due mostly to the additional cost. However, some users prefer hydraulic operation in smaller sizes also, to get the advantages of fluid operation without the use of air.

(*c*) There is no upper limit in size for air operation, but when high pressures are utilized, air cylinders and valves get quite bulky, operation is slower and air consumption is high and expensive.

Taking all factors into consideration, the average installation will be air-operated up to about 300 kva.; between 300 and 500 kva., about equally divided between air- and hydraulic-operated; and above 500 kva., hydraulic.

One other factor should be taken into consideration: the much faster follow-up of air as compared to oil. Due to its compressibility, the response of air on the piston is practically instantaneous, whereas, due to the incompressibility of oil, its response is slow, because this motion must be transmitted throughout the hydraulic system. This is particularly vital on short time welds, such as used on stainless steel, aluminum and other non-ferrous metals.

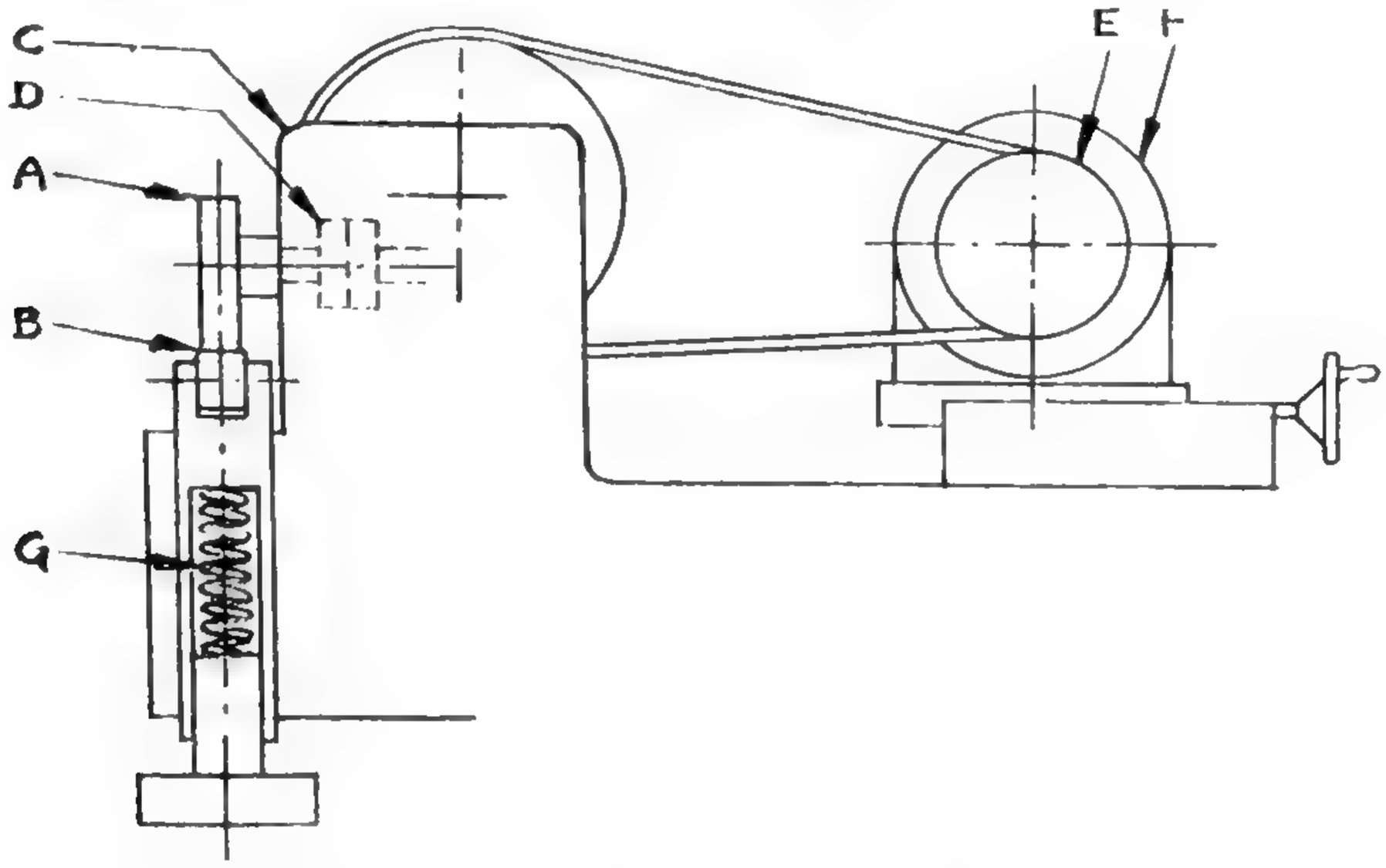


Fig. 2 (*b*).—Motor-Operated Welding Head

A, Welding cam; *B*, Cam roller; *C*, Gear box; *D*, Clutch; *E*, Variable speed pulley; *F*, Motor; *G*, Welding spring; *H*, Return spring (not shown); *J*, Timing cams (not shown); *J*, Initiating switch (not shown).

Toggle operation, formerly quite generally used, has practically disappeared, except in some cases to reduce cylinder size while obtaining high pressures. It should be noted, however, that this results in no air saving because the reduction in cylinder bore is offset by the increased stroke.

General Press Welding Machine Construction.—Because of manufacturing economics press welding machines are designed and built on the unit principle. The same frame (with some variations in drilling, etc.) will be used for two or three different kva. ratings and for all types regardless of throat depth, method of operation, etc. Some of these variations will be considered further, with respect to their effect on overall design.

Operating Head.—Since most manu-

facturers employ only one type of head construction on any given model, this need not be considered as a variable. The various types are shown in Fig. 3.

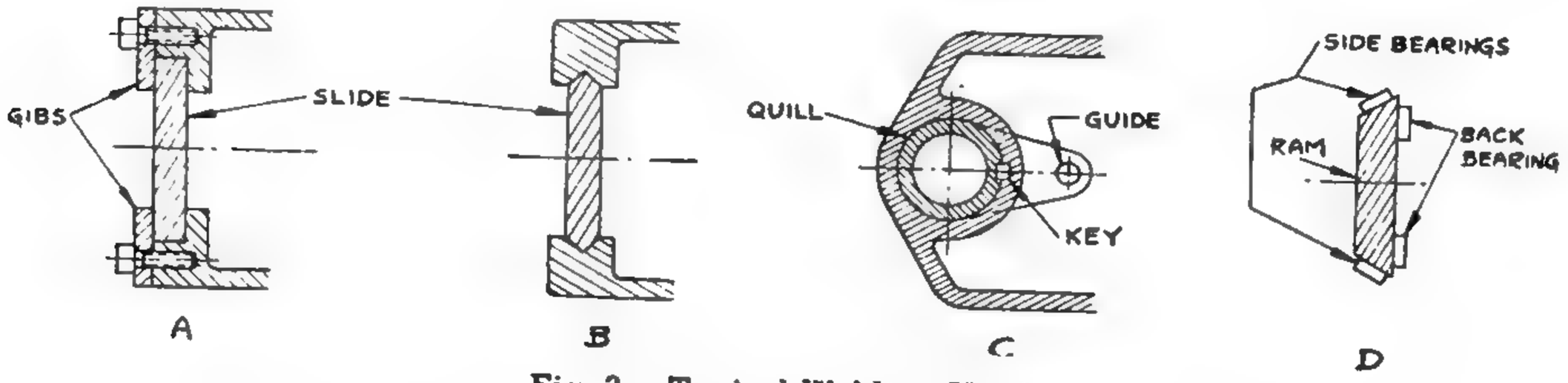


Fig. 3.—Typical Welding Heads

A, Rectangular slide; *B*, Vee slide; *C*, Quill; *D*, Anti-friction, or roller bearing.

Horns and Platens.—Projection welding machines employ tables or platens on which are mounted dies, fixtures and other tooling. These usually have standard T-slots for mounting. It should be noted here, that the horns, platens and lower knee determine the difference between spot and projection welding machines. The throat depth on any welding machine is the distance from the center-line of welding electrode to the frame of the machine. Thus, the same machine will have one throat depth as a projection welding machine and a greater throat depth as a spot welding machine. This can be seen by reference to Fig. 2(*a*). The center-line of the platens, the ram and air cylinder are all the same. Therefore, the distance from this center-line to the faced ways or frame of the machine is the projection welding throat depth. On standard machines the spot-welding electrodes extend 6 in. in front of this center-line. This is true whether platens are used or not. This 6 in. should not be exceeded because the head is not designed to take any greater offset load.

Projection and combination machines have a knee supporting the lower platen and are provided with a vertical adjustment. This knee may be cast iron, steel, copper, bronze, etc., depending entirely upon the design.

Spot-welding machines usually substitute a lower horn comparable to that used on rocker-arm machines for the lower knee, to reduce cost. This may be column or square mounted, but is always vertically adjustable.

Mechanical Principles—Air-Operated

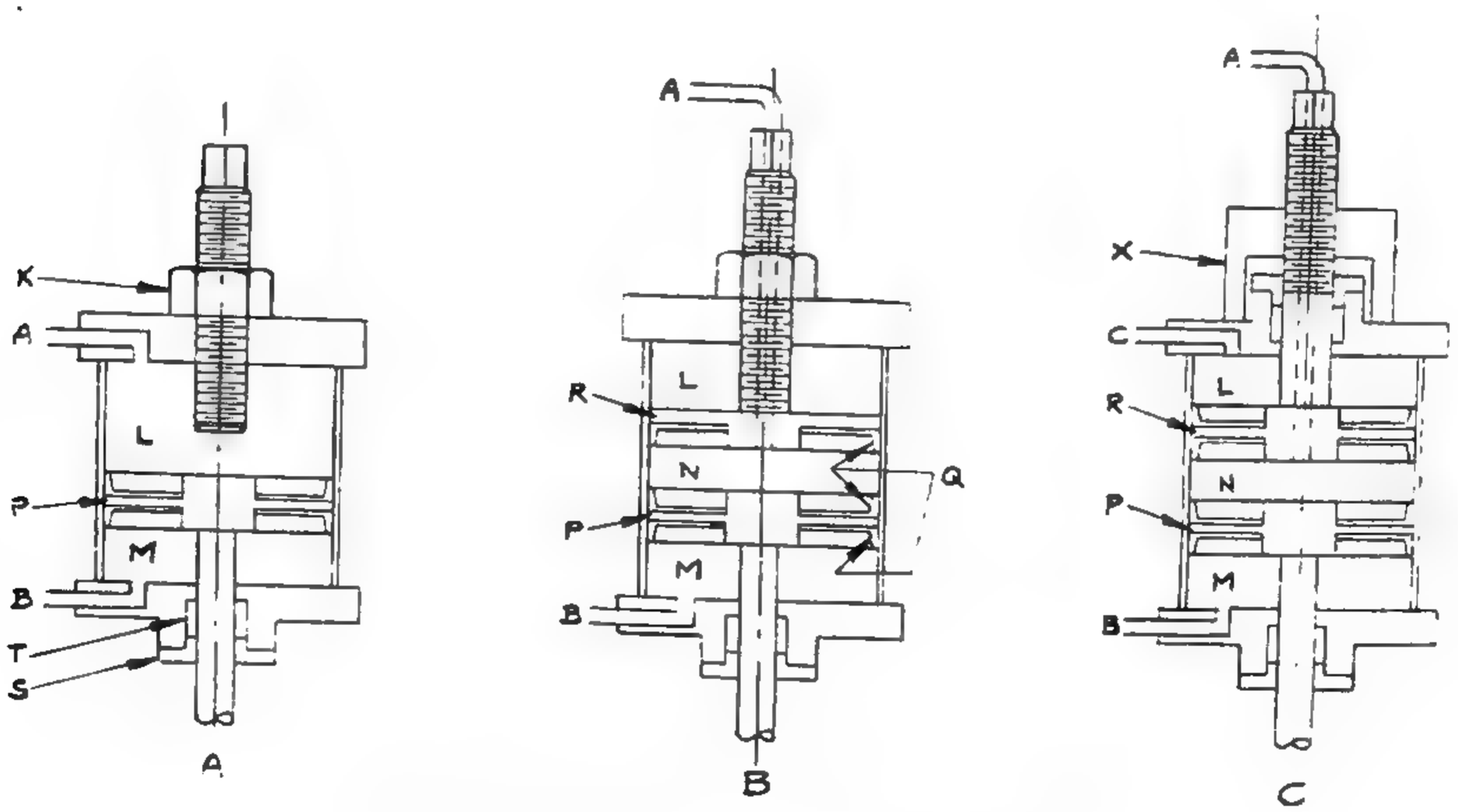


Fig. 4.—Standard Air-Operating Cylinders

Machines.—Air-operated press welding machines are usually of the direct-acting type, in which the pressure exerted by the piston becomes the welding force. One exception to this is the case where an air lock is used. Three general types of air cylinders are used, as follows (see Fig. 4). On all three types, air is admitted at Port *A* for the pressure stroke and exhausted at Port *B*.:

A. Fixed Stroke cylinder with stroke adjuster added. The stroke adjuster *K* satisfactorily limits the return stroke, consequently the point opening.

B. Adjustable stroke cylinder with dummy piston *R*.

C. Adjustable-retractable stroke cylinder. On this type, a third port *C* is added. If air is admitted through this port to chamber *L* at a slightly higher than operating pressure (in chamber *N*), piston *R* will remain in a position determined by the stop *X*. This determines the operating-point opening. By exhausting the air from chamber *L* through a separate 3-way valve, when piston *P* is returned it will carry piston *R* with it to the full available stroke of the cylinder. Re-admission of air at port *C* will again return piston *R* to its preset position, since the pressure in chamber *L* is slightly higher than in either chamber *M* or *N*. Speed control valves or cushions are usually used to check shock and control the operating speed.

Air Locks.—An air lock is a device inserted in the head of the machine to regulate the welding force and may be used with any type of operation. Its principal advantages lie in its ease of pressure regulation and, in some cases, the elimination of static packing friction.

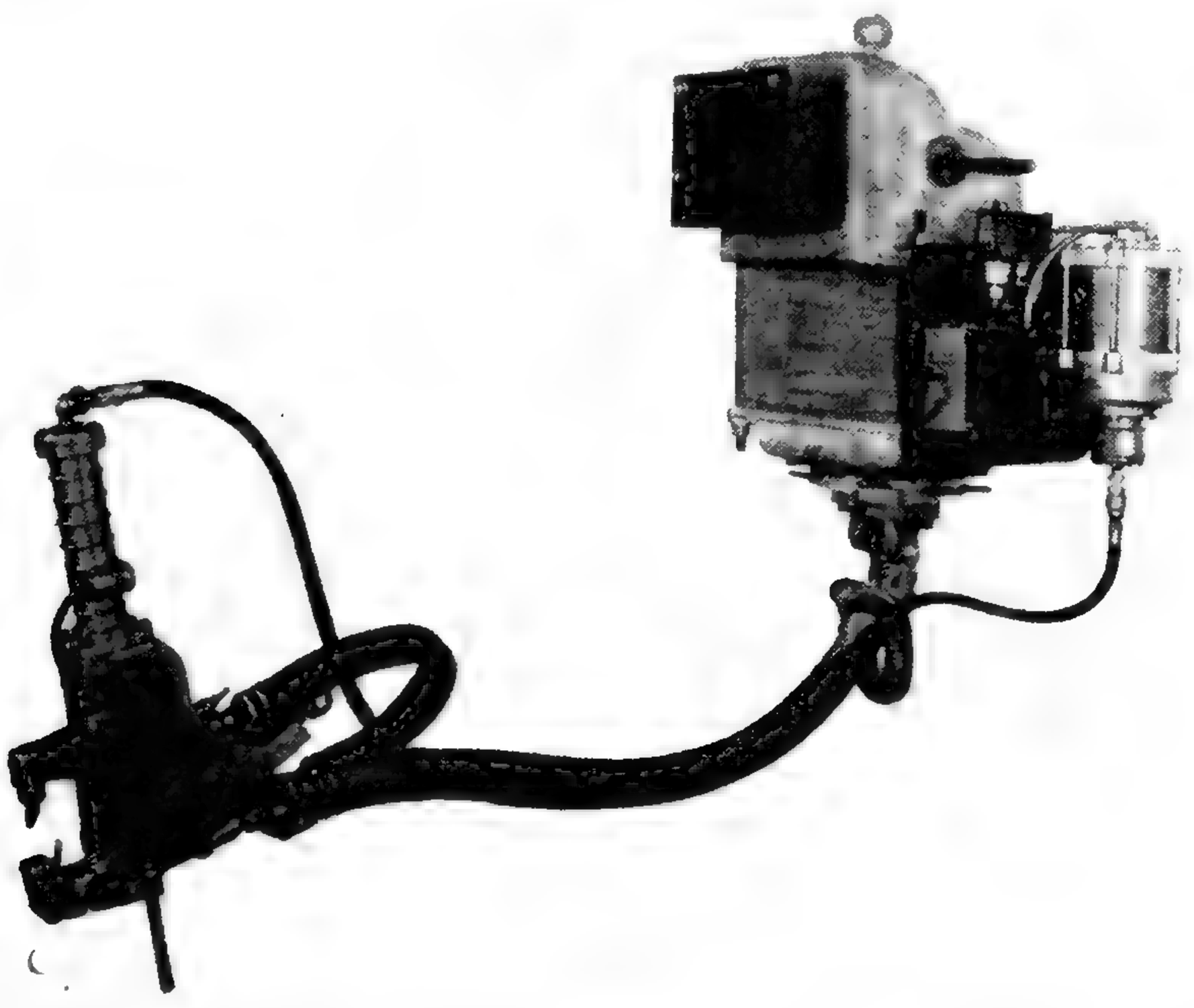


Fig. 5.—Hydraulically Operated Portable Welding Gun with Low Reactance or *Kickless* Cable

Mechanical Principles—Motor-Operated Machines.—Fig. 2 (*b*) shows the elements of a motor-operated machine. Usually the drive is interchangeable with the air or hydraulic cylinder on the same head, but provisions must be made in the head for a spring or an air lock. Like all mechanical drives, the only way the stroke can be changed is to change the cam.

Mechanical Principles—Hydraulic Machines.—The operation of a hydraulic machine is much the same as that of an air-operated one. The air cylinder with maximum operating pressure of 80 psi. is re-

placed by a hydraulic cylinder with maximum pressure of 1000 psi. Any type outlined in Fig. 4 may also be used for hydraulic operation.

In the simplest type of hydraulic system, a constant-speed motor drives a constant-pressure, constant-delivery pump whose output pressure is adjustable by means of an adjustable relief valve. This oil delivery is valved to and from the operating cylinder with a four-way valve the same as in an air system. Auxiliaries include a sump, filter, cooling coils, gage and sometimes an accumulator.

Portable Welding Machines

A standard portable welding machine consists of three main elements:

1. Transformer and regulator.
2. Secondary cable.
3. Welding head or gun.

A typical complete portable machine is shown in Fig. 5. The transformer is similar to any other resistance-welding transformer, except that on account of the much greater secondary losses to the gun, it must be wound for a considerably higher secondary voltage—on the order of two or three times as high for a given kva. rating. To accomplish this without an excessive core weight, the secondary is usually provided with 2, 3 or 4 turns so that the voltage per turn, which determines the size of the core, is no more than for any other type machine.

The secondary cable is now almost exclusively of the concentric or *kickless* type. In this, the two conductors are intertwined in such a manner that reactance is almost eliminated. However, to reduce bulkiness as much as possible, they are operated at extremely high current densities, which in turn necessitates thorough water cooling.

The welding gun is usually specially built for each job although it has been possible to standardize a few types. Guns may be hand, air or hydraulically operated.

The hand type is used only on very small units, such as *tongs* used by jewelers, etc., and for resistance brazing. The choice between air and hydraulic operation is generally determined by the pressure requirements. Since it is desirable to keep the weight of the gun as low as possible, hydraulic operation is preferred except for the smallest sizes.

Hydraulic guns are supplied with oil from a booster mounted on the transformer. This booster consists of an air cylinder having a piston area approximately twelve times as great as a hydraulic piston to which it is directly connected. A three- or four-way air valve operates the air cylinder, which in turn operates the hydraulic cylinder and gun-operating cylinder connected by flexible hydraulic hose taped or strapped to the secondary cable. Electrode force is controlled by the air pressure, the same as on any air-operated machine.

Many interesting variations of portable machines, such as *poke* or *stick* guns, pry-bar and short-circuiting guns are widely used, but space does not permit further details.

TYPES OF MULTIPLE-SPOT WELDING MACHINES

Multiple-spot welding machines may be grouped into three general classes or types:

1. Pressure-controlled (hydromatic).
2. Commutator-controlled (ultraspeed).
3. Multiple transformer.

Figures 6, 7 and 8 show typical machines of each of these three types. Machines in all these classes are considered as special, designed and built for a specific job.

The pressure-controlled machines were the first of the three types developed and consist of a number of hydraulically-operated welding guns mounted in a framework or fixture—one gun for each spot required for a single assembly. Sometimes a gun is required for each side of the spot, in which case the two guns are operated simultaneously. Most applications, however, permit a common mandrel or bar to be used for the lower electrode. Each gun is connected by flexible bands to a common busbar connected to the transformer. Each gun is hydraulically connected through an air- or motor-operated distributer valve to a hydraulic pump, which actuates each gun in proper sequence. At the same time an initiating switch, synchronized with the valve, initiates the welding current with each gun movement. While all guns connected to a common busbar are energized at once, only the one gun in contact with the work can carry current.

Commutator-controlled machines may be somewhat similar to the hydromatic ma-

chines in appearance and construction, but differ in operation. In this type of machine, the guns are located to suit each spot, but are hydraulically connected by a single valve to a hydraulic header fed from a pump. Electrically, however, each gun is connected to a segment of a commutator-controlled switch. In operation, all guns mechanically contact the work simultaneously under full pressure, but welding current is fed to only one gun at a time through the commutator-controlled switch.

The multiple-transformer type has now largely superseded the other two. In this type, guns, placed as required, are hydraulically connected to a common header as in commutator-controlled machines. But each gun or pair of guns is connected to an individual transformer, and all welds may be made simultaneously. Most transformers built for such service are provided with two secondaries, permitting two guns for each transformer and, in many cases, two welds may be made in series, allowing four spots per transformer in which case four guns are used for each transformer.

The multiple-transformer type of machine has many advantages:

1. It is much faster, as welds are made simultaneously. (If available power is lacking, the transformers can

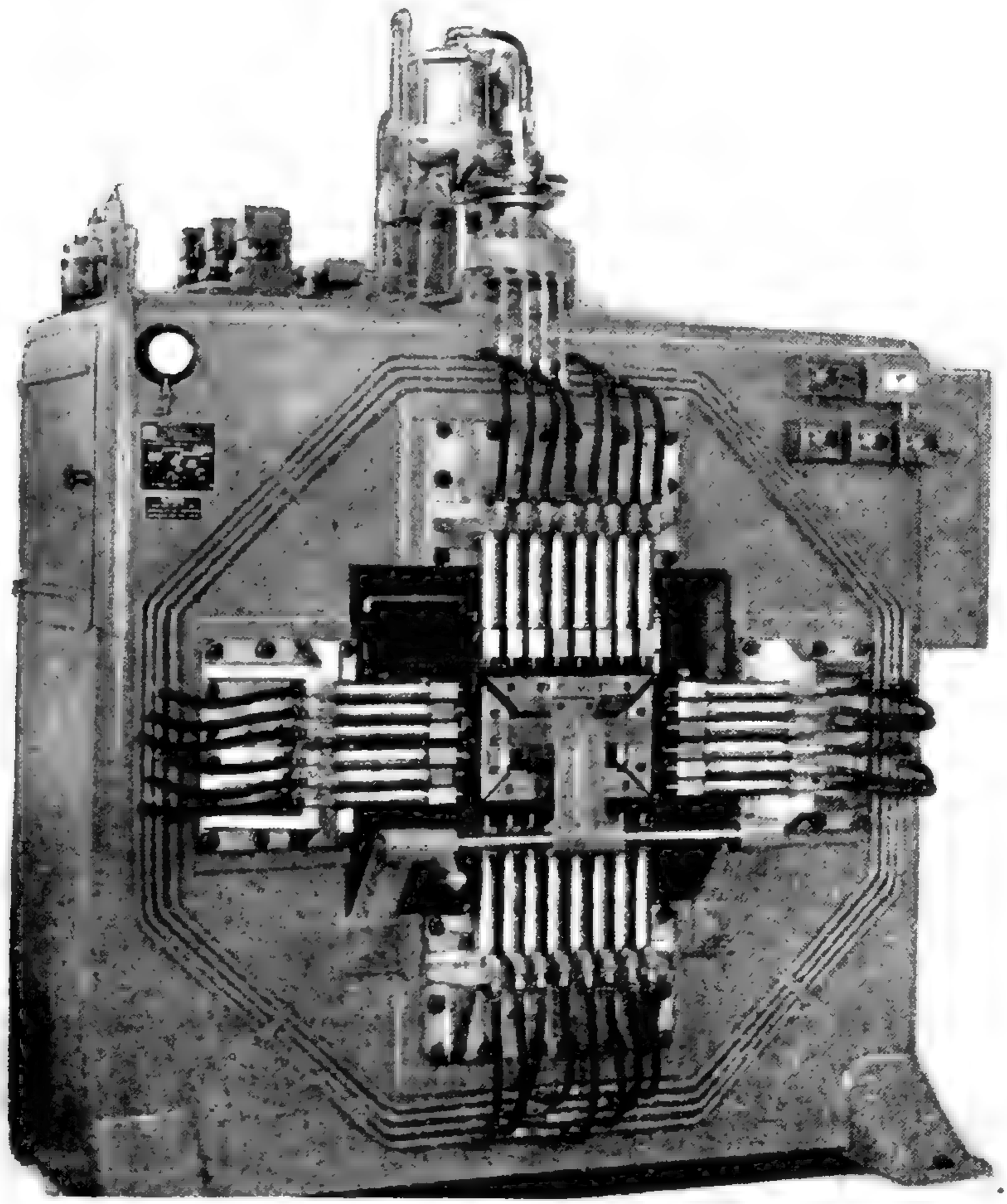


Fig. 6.—Pressure-Controlled Spot-Welding Machine with 28 Guns

...ing sequence, through electrical ...

... is simpler in construction as it ... other distributing valve or switch ... It permits much more uniform ... distribution of current to each weld ...

TYPES OF ROLLER SPOT- AND SEAM-WELDING MACHINES

A roller spot- or seam-welding machine is similar in principle to a spot welding

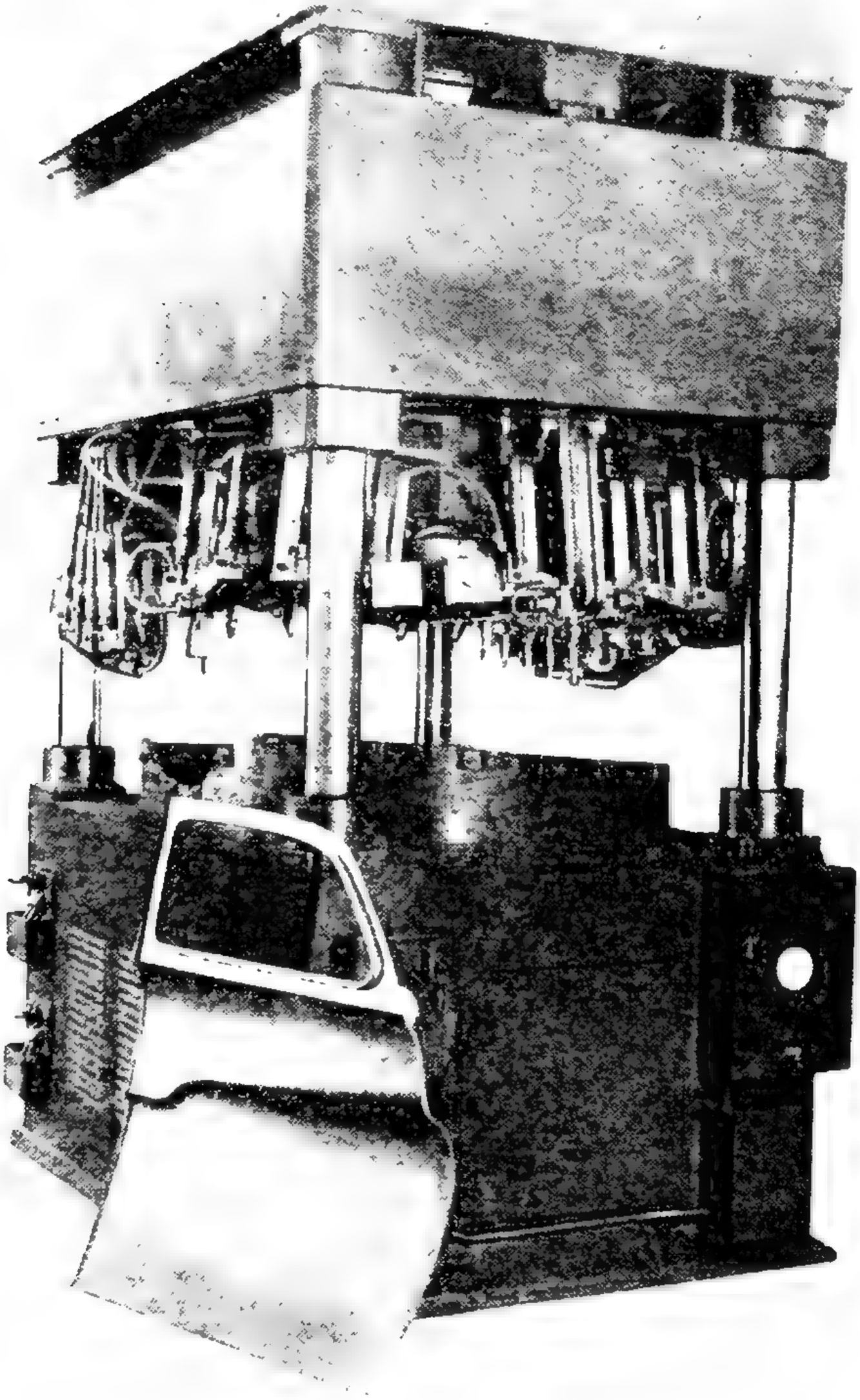


Fig. 7.—Commutator-Controlled Spot-Welding Machine with 65 Guns

Very large users of this type of equipment have found it possible to stock guns, transformers and other more or less standard units, and build up special machines from these stock items

machine, except that it is provided with wheel electrodes permitting work to be fed into it somewhat similar to a sewing machine The only difference between a roller spot and a roller seam weld is the

spacing between individual spots or welds, and both are performed on the same machine.

The essential elements of a standard seam-welding machine are:

1. Main frame, containing welding transformer and regulator.
2. Welding head, consisting of air cylinder and head slide mechanism.
3. Welding wheels, bearings and secondary connections to transformer

head to the piston rod is either adjustable, or an adjustable stroke cylinder is provided. In addition, the lower electrode with its mounting arrangement (arm, table, knee, etc.) is sometimes adjustable. This lower adjustment is used when it is necessary to maintain the work at a constant level above the floor.

Standard seam welding machines have one or both electrodes power driven, usually by means of a constant-speed electric

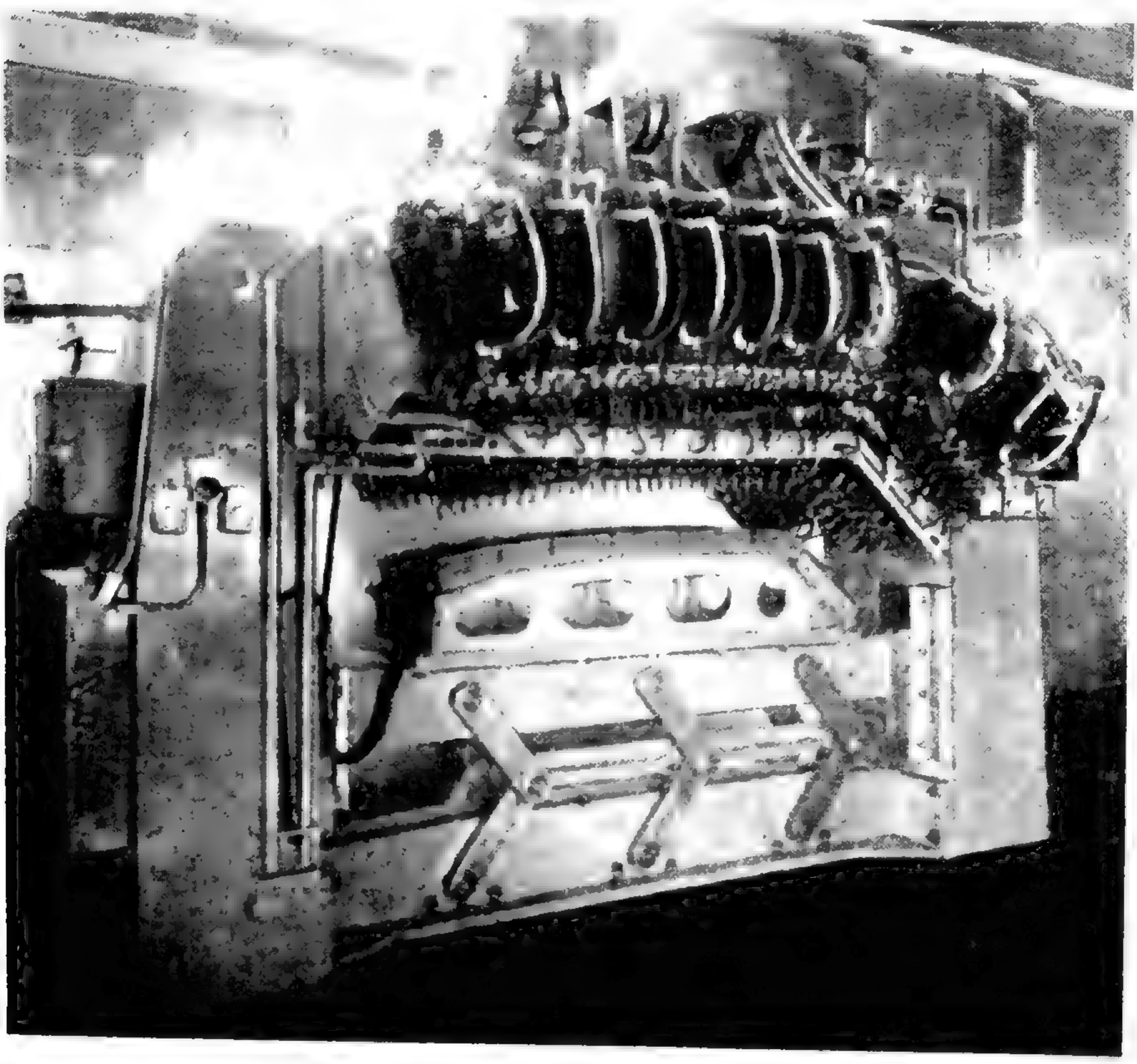


Fig 8 —Multiple-Transformer Spot-Welding Machine

The main frame with transformer, regulator, welding head, air cylinder, etc (1 and 2 above), are essentially the same as for standard direct, air operated, press type machines previously described Seam welding machines today, almost without exception, utilize a direct-acting air cylinder as a means of pressure application Since provision must be made for wear of the electrodes, the connection from the

motor through a variable speed reduction drive

There are three general types of seam welding machines:

1. Circular, in which the plane of the electrode discs is at 90 deg to the throat of the machine This type is used for flat work where the seam may be quite long. It is also used for all types of circular work such as welding seals of containers, etc

2. Longitudinal, in which the plane of the electrode discs is parallel with the throat of the machine. This type is used for such applications as welding the longitudinal seams in containers and other work of a similar nature.

3. Universal, in which the wheels may be set in either the circular or longitudinal position. This is accomplished by the use of a swivel-type upper head in which the wheel and its bearing can be swivelled 90 degrees. The lower mounting may consist of two interchangeable lower arms, or both may be permanently attached to the machine by means of hinges or a swinging column so that either one may be swung into place.

Figure 9 shows the electrode arrangements for standard-type machines as well as the methods of drive.

Throat Depth

Standard seam-welding machines, like press-welding machines, are classified by throat depth. The nominal throat depth is generally the distance from the electrode contact point to the frame of the machine measured parallel to the arms. However, this entire distance may not be usable. This is particularly true when welding cylinders or similar work. It is also generally true on universal types of machines.

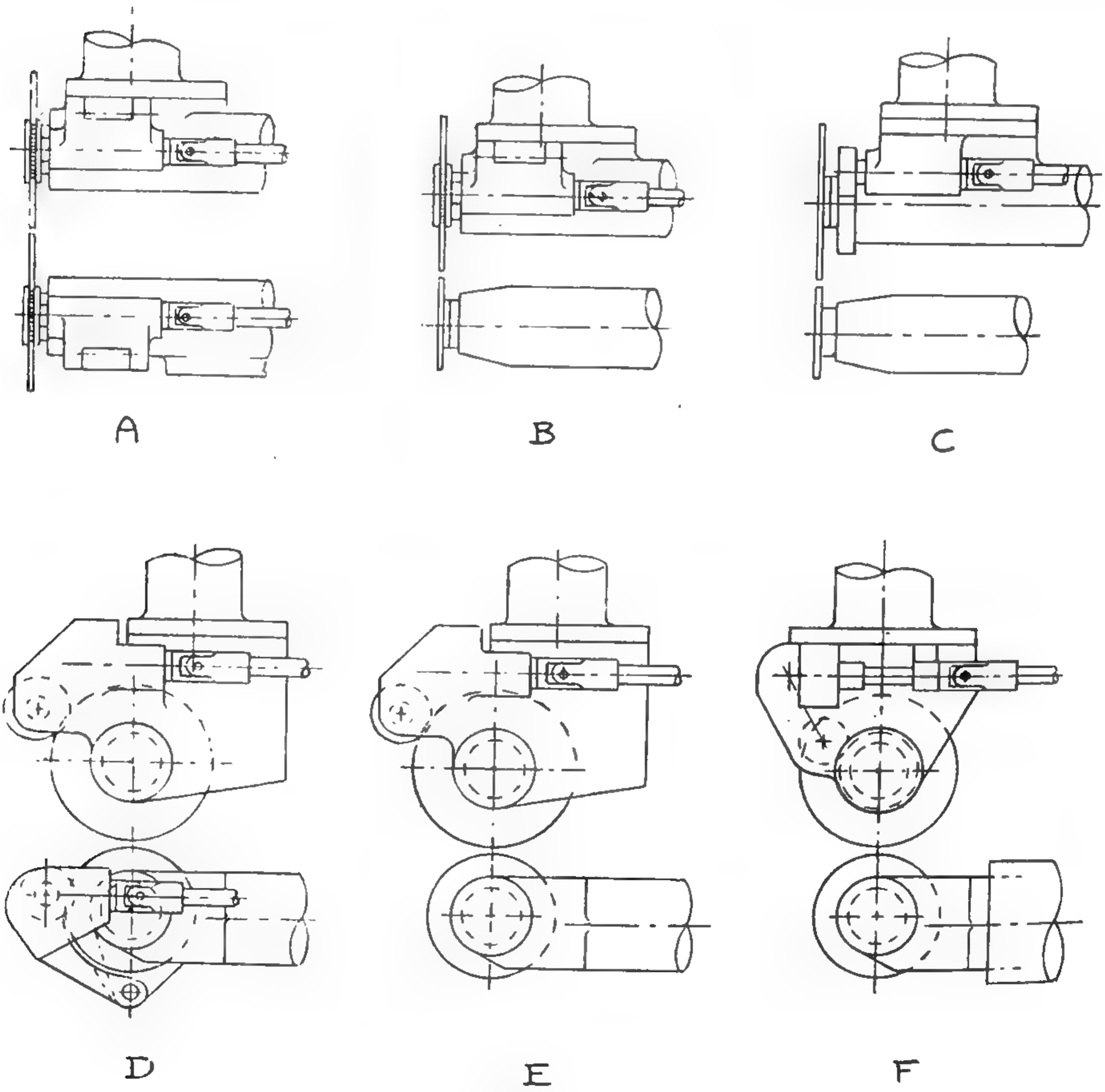


Fig. 9.—Types of Standard Seam-Welding Machines and Arrangements of Drive

A, Circular, double knurl or friction roll; *B*, Circular, upper knurl or friction roll; *C*, Circular, upper gear; *D*, Longitudinal, double knurl or friction roll; *E*, Longitudinal, upper knurl or friction roll; *F*, Universal, upper gear.

Therefore, the usable throat depth should not be confused with the nominal throat depth.

Driving Mechanism

Two general types of drive are commonly employed:

1. *Knurl or Friction Roll.* This type has either the upper or lower or both electrodes driven by a friction wheel at the periphery. These friction rolls sometimes have knurled teeth cut in them, in which case they are known as knurls or a knurl drive. For most work, this is the preferred type of drive, as the speed is maintained constant regardless of the electrode diameter, and the knurl or friction roll continuously trims the wheel, thus preventing its *mushrooming*. The knurl is used on coated materials, such as galvanized steel, terne plate, scaly stock or any application where the electrodes are likely to pick up material from the stock being welded. Where the nature of the work permits, both electrodes should be knurl driven, as this provides a more positive drive and lessens the possibility of skidding.

2. *Gear Drive.* Generally speaking, this type is less desirable than the knurl drive, because the welding speed decreases as the electrode wears. However, this can be compensated for by adjusting the variable speed drive. Another objection is that only one electrode can be driven, otherwise some skidding will occur.

The most important application of the gear-driven machine is welding heads in small diameter containers. The very nature of standard seam welding machines requires a minimum distance between electrode centers, and if one of the electrodes must be small to get into the container, the other must be correspondingly larger to maintain the required center distance. If the ratio of the two electrode diameters exceeds about 2 to 1, the smaller one should be the driving electrode, otherwise excessive skidding will result. Small diameter electrodes cannot successfully be knurl driven, but are readily gear driven in the circular but not the longitudinal position. In some cases, where it is desirable to gear drive one wheel, the other can be equipped with an idling knurl.

Special Seam-Welding Machines

Many types of machines have been developed for special purposes, and these can generally be grouped as follows:

1. *Traveling Electrode Type.* The work is clamped or otherwise held fixed over a mandrel or shoe of some type while an electrode is passed over it. In this case, the mandrel or shoe replaces the lower electrode. The upper electrode is moved by an air or hydraulic cylinder or by means of a motor-driven screw. Sometimes two upper electrodes are used, operating in series. This is a very desirable type as it permits an efficient secondary circuit. Figure 10 shows a typical traveling-electrode type machine.

2. *Traveling Fixture Type.* In this case, the upper electrode is stationary, with the fixture and work being moved by an air or hydraulic cylinder or a motor-driven screw. Here again multiple electrodes can be used to advantage. Figure 11 shows a typical machine of this type.

3. A very important type of seam welding machine is the type used for continuously welding the longitudinal seams of piping or tubing. This is a butt seam weld, but welding current is applied to the two edges of the seam by roller electrodes or wheels. Strip steel is fed into a series of forming rolls which progressively form it into a tubular shape, then force it through the welding electrodes where it is welded, shaved and then cut to length.

4. *Can welding machines* form another group of semi-continuous welding machines. Rolled drums are fed through electrodes and held in place by hour-glass rolls. With the aid of automatic feeding equipment, barrels, drums or other containers can be welded on practically a continuous basis.

5. *Portable seam welding machines* can be used in some cases where the work is too bulky to be handled through regular electrodes. In this case, the work is clamped in a fixture while a portable welding head is moved over the seam. The head consists of a pair of motor-driven (usually air-motor) wheels with their bearings and an air-cylinder mechanism for providing the necessary pressure. The welding current is supplied by a stationary transformer through flexible secondary cables. Due to the high duty cycle of seam welding machines, these cables are quite bulky and should be kept as short as possible.

Fixtures

Work-holding fixtures are quite varied in design and construction, and space does not permit much description. One

of the simplest types is one which holds two plates or discs being welded around their periphery, used for toy wagon wheels, etc. This fixture consists of a spindle upon which the discs are placed, together with a suitable clamping device. During welding, the work rotates around the spindle, resulting in a circular weld.

A variation of this is one in which the spindle is carried on a pantograph, permitting its free motion in a horizontal plane. This type is used for welding out-turned flanges on non-circular assemblies, as for instance, automotive gasoline tanks.

A further refinement or variation is a

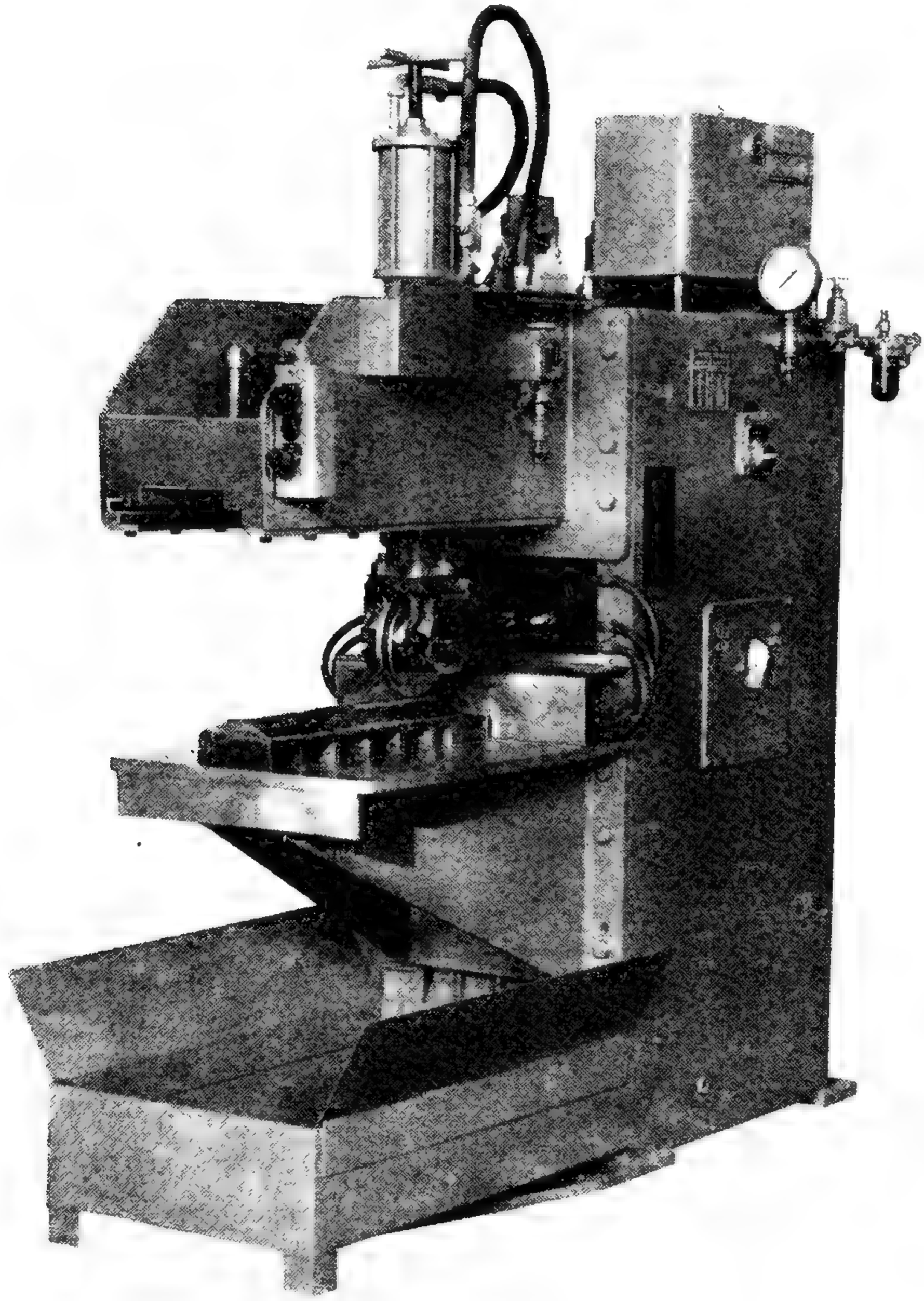


Fig. 10.—Traveling Electrode Type of Seam-Welding Machine

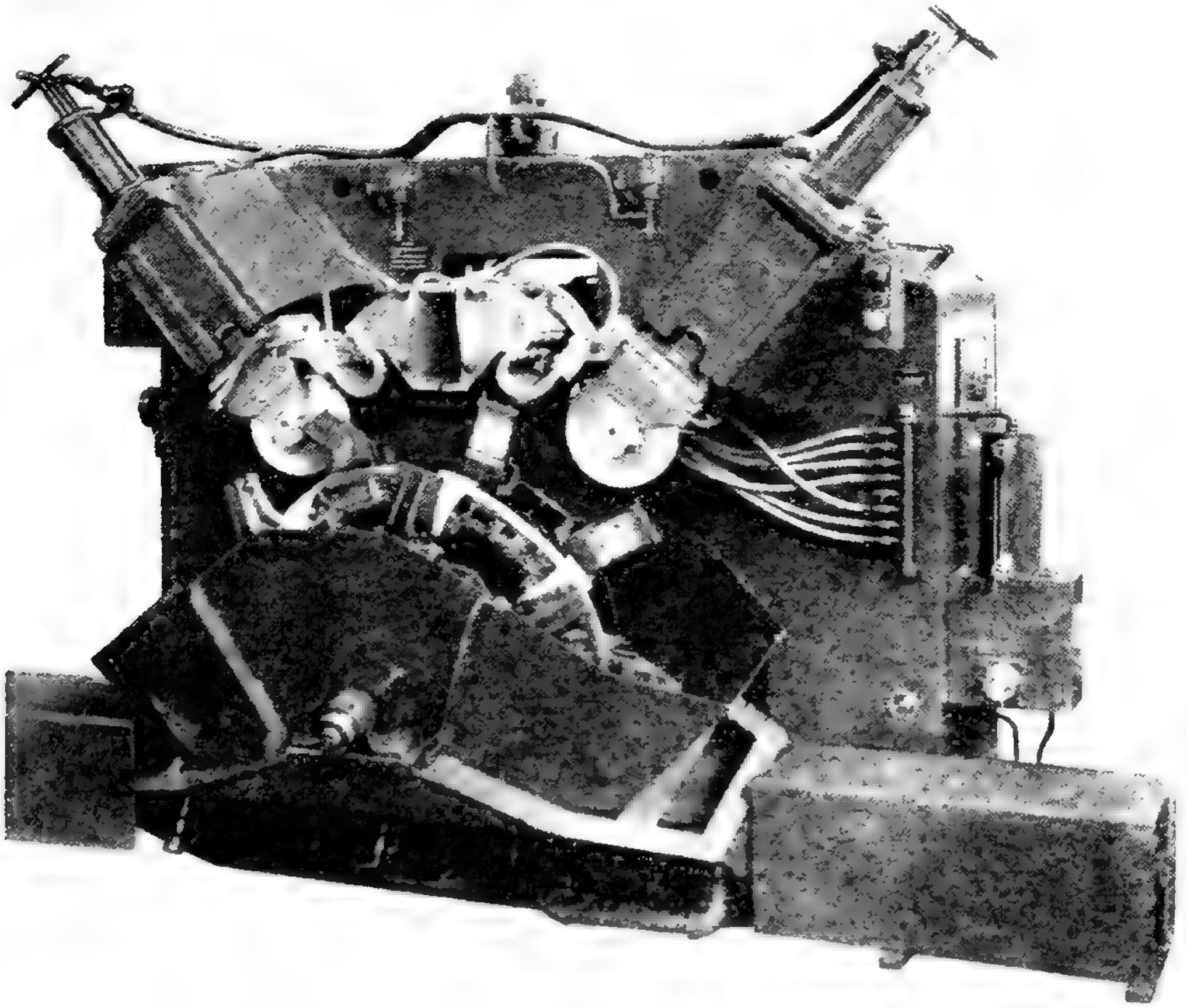


Fig. 11.—Traveling Fixture Type of Seam-Welding Machine

guided fixture, commonly known as an *iron-man* fixture which is shown in Fig 12. Here, the operator merely places the work in the fixture and starts the weld, after which the work is automatically guided and the weld completed without further attention

Cooling

One of the principal problems in seam welding is the proper cooling of the machine including the electrodes, bearings and secondary circuit. Of greater importance though, is the cooling of the work. Whenever concentrated heat is employed, as in seam welding, warpage and distortion are bound to take place. This warpage is minimized by cooling the work as fast as possible. Probably best seam-welding results would be obtained by making the welds under water, but the physical proportions of the work usually makes this impractical. The nearest substitute is sprays of cooling water provided for both upper and lower welding wheels and the work.

FLASH AND UPSET WELDING MACHINES

An upset weld is obtained by first bringing two pieces of metal into end-to-end contact under pressure, and then allowing current to flow from one piece to the other. A flash weld is obtained by first applying a voltage drop across the gap between two pieces of metal, and then bringing the pieces into contact so as to permit current to flow. Manually-operated machines may be used either for upset or flash welding without change. Air-operated machines are used for upset welds, while motor- or hydraulically-operated machines are applied to flash welding

Upset-Welding Machines

In principle, upset welding is quite similar to spot welding, except that the

nature of the work requires different handling. A typical upset welding machine consists of a machine having a set of clamps to hold the work and mechanical means to force the two pieces together. In modern machines, timing equipment is provided to synchronize the overall welding cycle (see Fig. 13).

The simplest type of upset welding machine is hand operated. In this machine the work is clamped in the dies and pressure exerted on the movable platen. Current is then applied, and when the ends of the work are sufficiently hot to upset under the applied pressure, current is cut off and the work removed from the dies. A limit switch may be used to automatically cut off the current when the upset has reached a predetermined amount, or, the current cut-off may be determined by means of a timing device.

Machines may be made automatic in operation by the substitution of springs or weighted levers for the hand lever. Either of these devices merely assures uniform pressure application. The weighted lever has been practically discontinued due to its inertia, but spring-

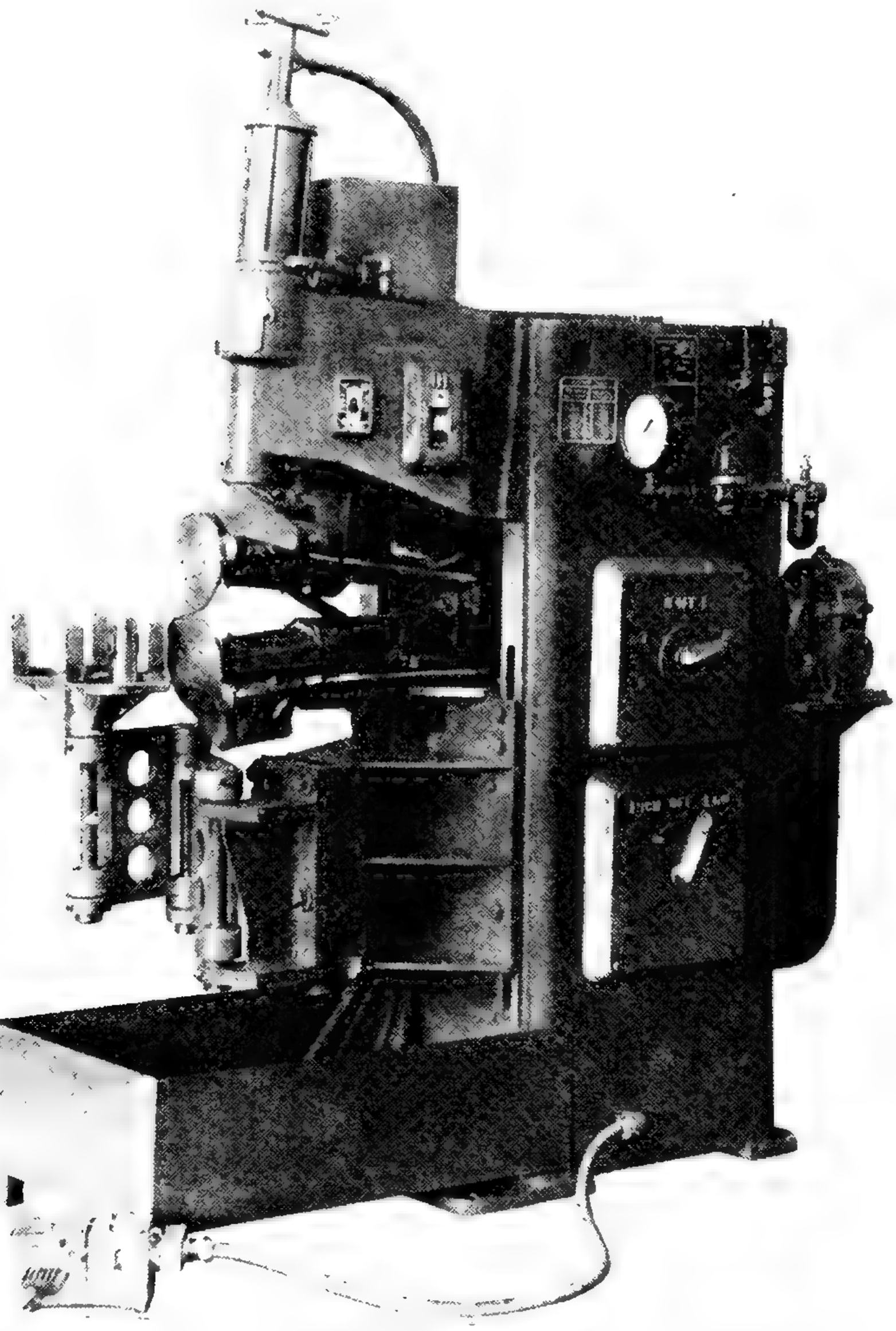


Fig. 12.—Standard Circular Seam-Welding Machine Equipped With *Iron Man* Type Fixture

operated machines are still used, usually in conjunction with an air cylinder.

Air- and spring-operated machines are quite successful on nonferrous work. The spring produces a quick follow-through necessary for this kind of work due to the short plastic range of the metal. Figure 13 shows a typical automatic upset welding machine.

If the machine is used exclusively on steel, the spring may be dispensed with, and in this case, the machine may be operated directly by a double-acting air cylinder.

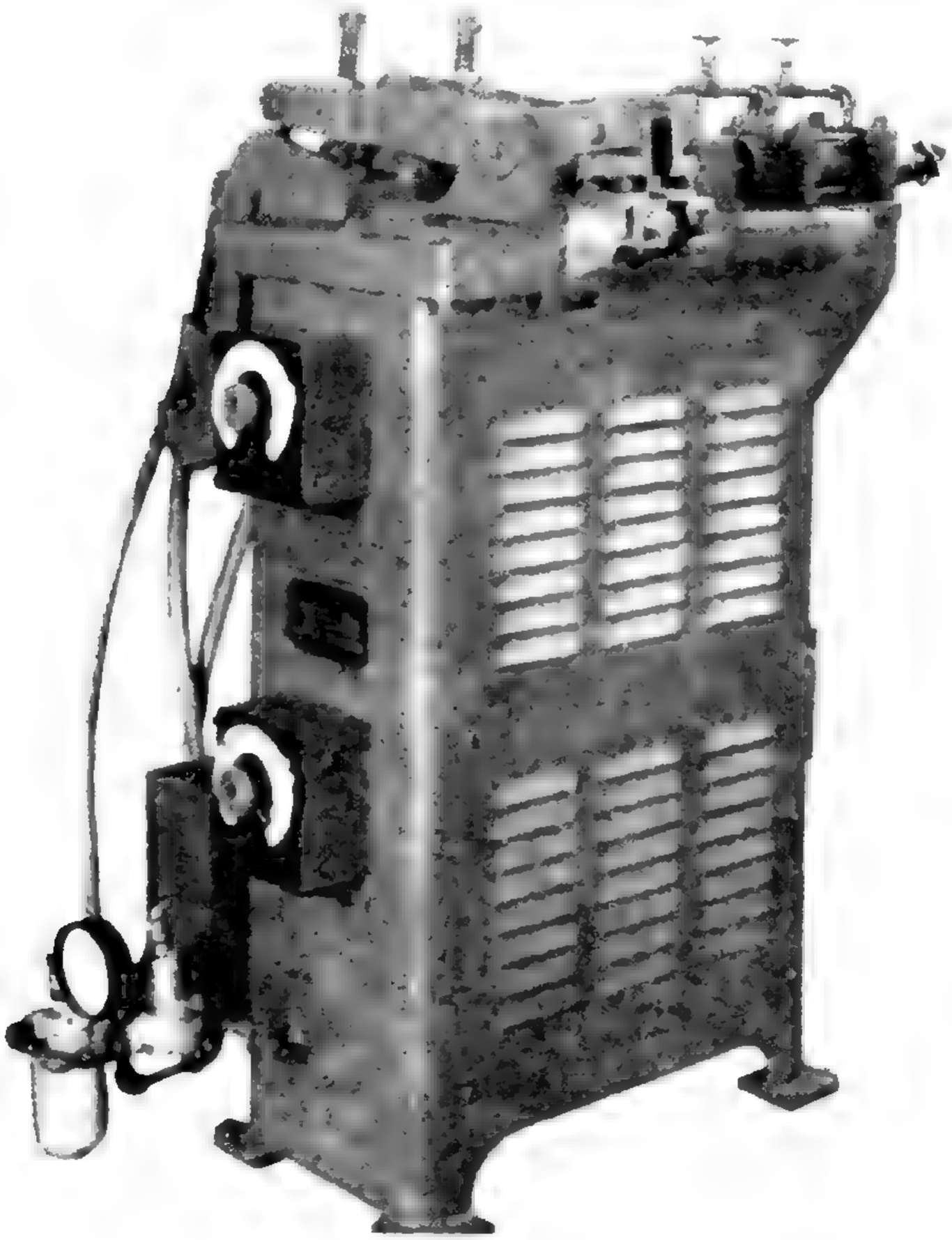


Fig. 13.—Air-Operated Automatic Upset-Welding Machine

By the use of relays, the operation is completely automatic and very fast. There are two methods of timing the weld either of which gives generally satisfactory results: by means of a limit switch on the platen or with an automatic timer.

Application.—The application of upset welding is limited to small wires, rods and bars such as refrigerator and stove racks, chain links and some tubular products. By modification, it is also applied to upsetting and forging operations.

Merely by reversing the action of the upset welding machine it performs an important function in the cutting of stranded wire cable. The cable is clamped in the dies where the cut is to be made, tension instead of pressure is applied to the movable platen and current applied. The current quickly severs the cable and at the same time fuses the strands together on each end to prevent their fraying. Machines are built for completely automatic operation—feeding the cable from a reel, measuring to an exact length, cutting off and stacking, all without any attention from the operator.

Flash-Welding Machines

General Construction.—A standard flash-welding machine consists of a main

frame open on top. At the one end at the top, the stationary platen is bolted to the frame but insulated from it by laminated phenolic sheet. This platen is usually non-adjustable, although it may be provided with a limited amount of adjustment to and from the movable platen. At the other end, the movable platen is mounted on suitable ways and connected to the upset mechanism. Both platens are usually of cast iron or steel and are arranged to accommodate copper terminals which connect to the transformer and also mount the welding dies. The transformer is located within the frame and the regulator is located convenient to the operator.

The width (front to back) of the frame and consequently the platens depends upon the width of the work (or the length of weld line). Upsetting force should be applied as near as possible to the line of work, both vertically and horizontally, in order to prevent unnecessary stresses from being transmitted through the movable platen ways. If the platens are wide, double cams or double cylinders should be used. It is also necessary to use double cylinders if large bars or tubes project beyond the end of the movable platen.

Upset Mechanisms.—Flash and upset movement on small machines (up to about 75 kva. or 1-in. cross section of steel) can be satisfactorily applied by a hand lever operating the platen directly or through a simple or compound toggle linkage. This type of upset is particularly adaptable for job shop and short production runs.

Large machines can also be hand operated through the medium of hydraulic power.

A motor-operated upset mechanism consists of a motor driving a speed reducer, on the slow speed shaft of which is mounted the welding or upset cam. This cam moves the platen either directly or through a lever. In some types of machines a multiple-tooth clutch is used to start and stop the cam for each welding cycle, while others use a start-stop motor with an auxiliary cam and limit switch to stop the motor and apply a brake at

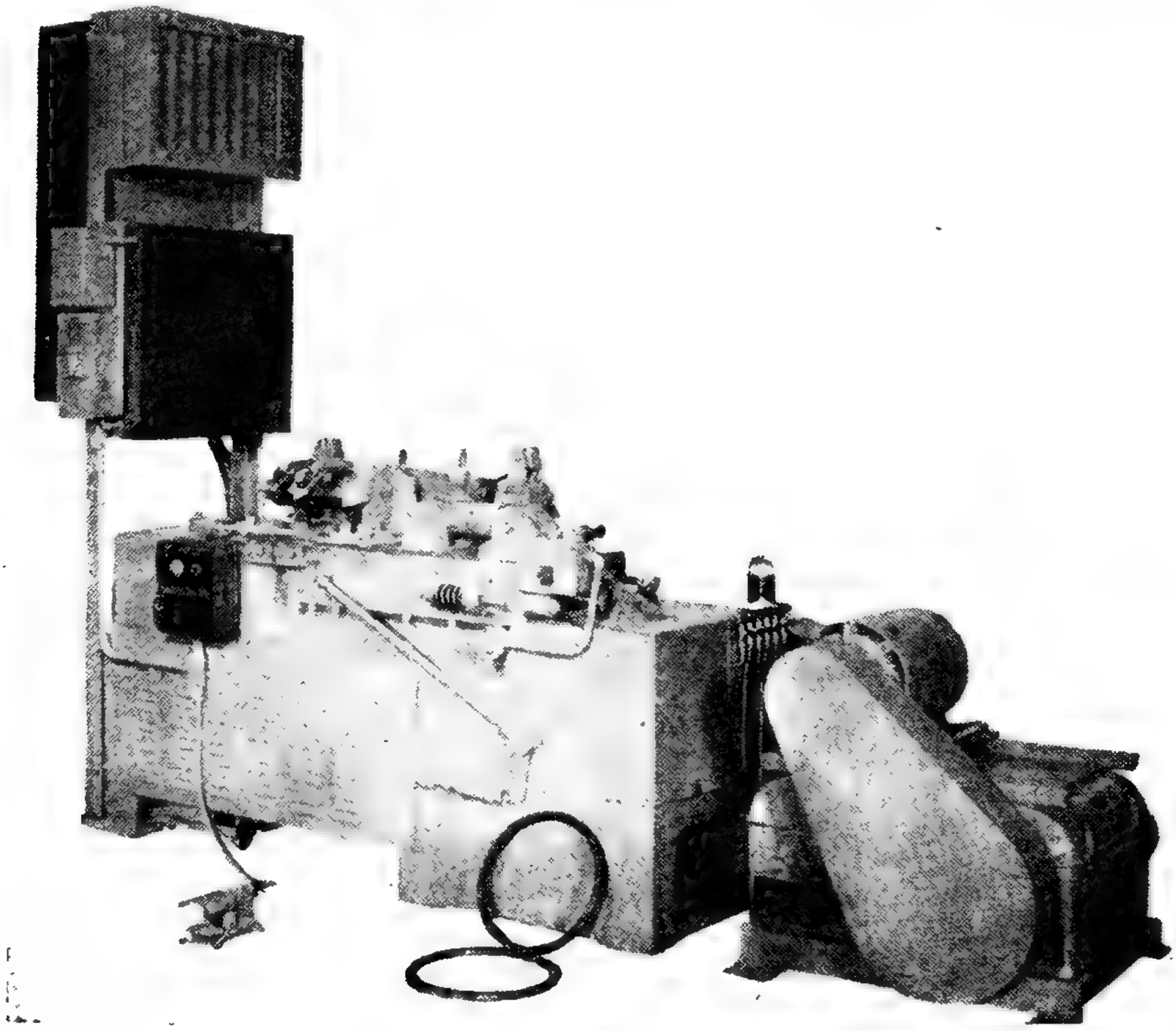


Fig. 14.—Motor-Operated Automatic Flash-Welding Machine Provided with Postheat Controls

the completion of the weld. The motor is started by a push button or other outside contact. Figure 14 shows a typical motor-operated machine.

The weld is initiated in clutch-type machines by manually tripping the clutch and with automatic disengagement. However, the engagement of the clutch can also be accomplished by a solenoid or air cylinder.

An auxiliary adjustable cam is also mounted on the camshaft to operate the welding contactor through a pilot switch.

The flashing action or motion of the movable platen must be controlled with reasonable accuracy, and this accuracy assumes increasing importance on high-speed machines.

General purpose machines require a very slow movement at the start of the weld with increasing speed toward the finish. It is not considered practical to obtain any variation in this flashing action, and if a variation is required, it is necessary to use interchangeable cams. A partial adjustment of total flashing travel is possible by using a stop to prevent the cam roller from going all the way back on the cam at the end of each weld.

The upset block, however, can be made adjustable, usually through the use of shims.

The connection from the cam roller to the platen is adjustable to provide an adjustable die opening or platen separation.

The welding speed or time of revolution of the cam is adjustable by means of a variable-speed transmission between the motor and speed reducer, or with a variable speed motor.

Hydraulic upset mechanisms are of two general types: manual and automatic. Both types employ one or two hydraulic cylinders to operate the platen directly. The manually-operated type consists of a motor-driven hydraulic pump with a hand-operated valve to control the flow of oil to and from the cylinder.

The automatic type consists of a hydraulic pump with a cam-operated flow or needle valve to control the flow of oil to and from the cylinder, together with the necessary auxiliary valves, gages, etc. Sometimes, an accumulator is used to supply the increased demand for oil at upset. Figure 15 shows a large, fully automatic, hydraulic flash-welding machine with double cylinders and air-hydraulic accumulator for fast upset.

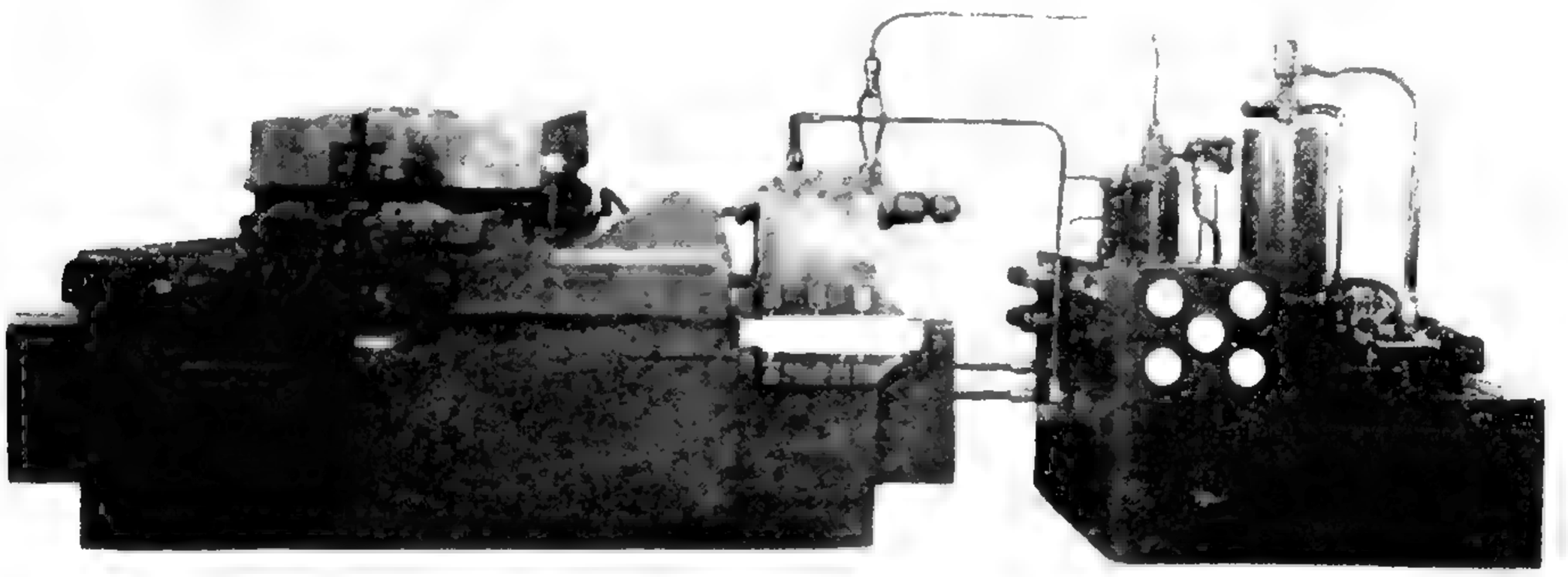


Fig. 15.—Automatic Hydraulic Flash-Welding Machine Showing Pumping Unit with Accumulator for Fast Upset

Unit is also provided with a separate pump for clamping so that independent clamping and upset pressures may be used.

Most automatic hydraulic machines can also be adapted to hand or semi-automatic operation. This permits the weld on very large sections to be started manually and completed automatically.

Transformer and Regulator.—The transformer is essentially the same as that used on other resistance welding machines with secondary pads suitably arranged. Some suitable barrier is provided to keep flash and dirt out of the windings. The regulator is suitably mounted on the frame of the machine to be easily accessible to the operator.

If a range of secondary current and voltage greater than that possible with a

tapped transformer is necessary, an auto-transformer may be provided.

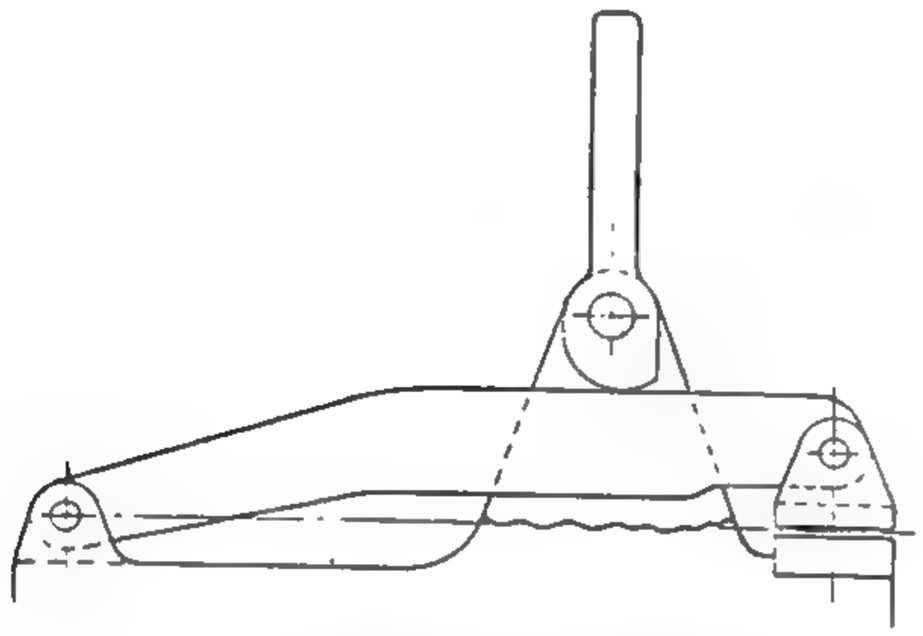
Clamping Mechanisms and Fixtures.—Many styles of clamping fixtures, several of which are shown in Fig. 16, have been developed for various types of work, and these may be grouped into two general types as follows:

(*a*) Vertical: This type has a vertical action, and the upper die or jaw may be hinged at one end, in which case, it is called an *alligator clamp*, or the upper die may operate in a slide.

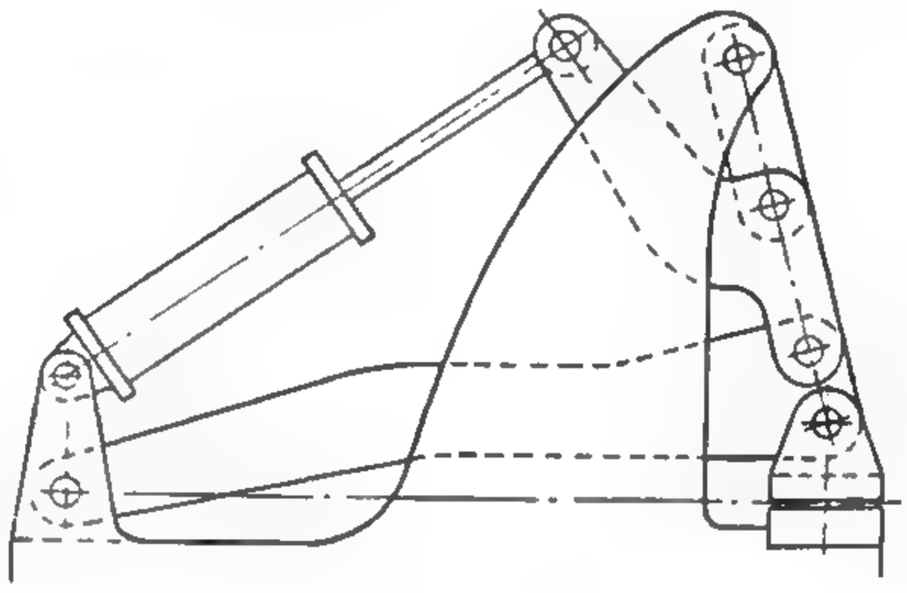
Where the nature of the work permits, the alligator type is preferred due to its greater simplicity, especially in large sizes. However, due to difficulties in maintaining uniform clamping pressure over the entire width, its use is limited to a weld line of about 20 inches. When the weld line exceeds this, a beam-type fixture is usually used. In this type, the beam is hinged in the rear and latched in front; then both front and rear are operated by air or hydraulic cylinders.

The alligator fixture is commonly used for strips of all kinds (not exceeding 20 in.), bar stock and special sections. Closed bands such as automotive rims require this type of fixture.

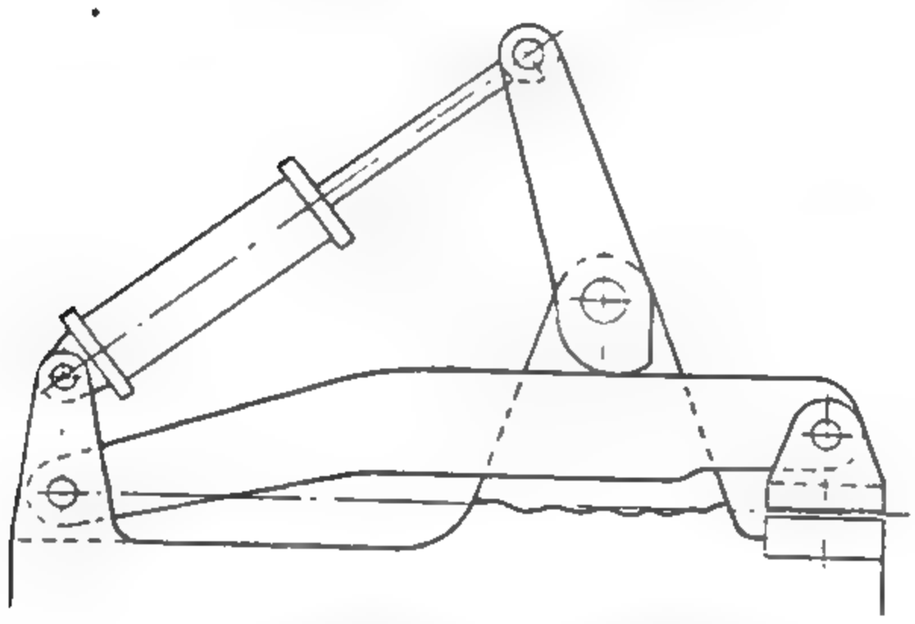
The slide-type fixture is adaptable



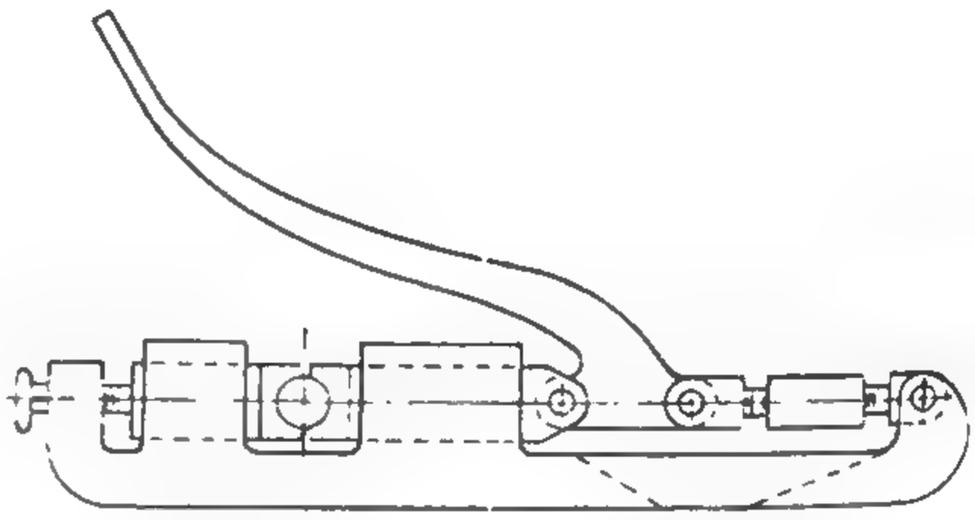
A. Vertical, hand-cam operated.



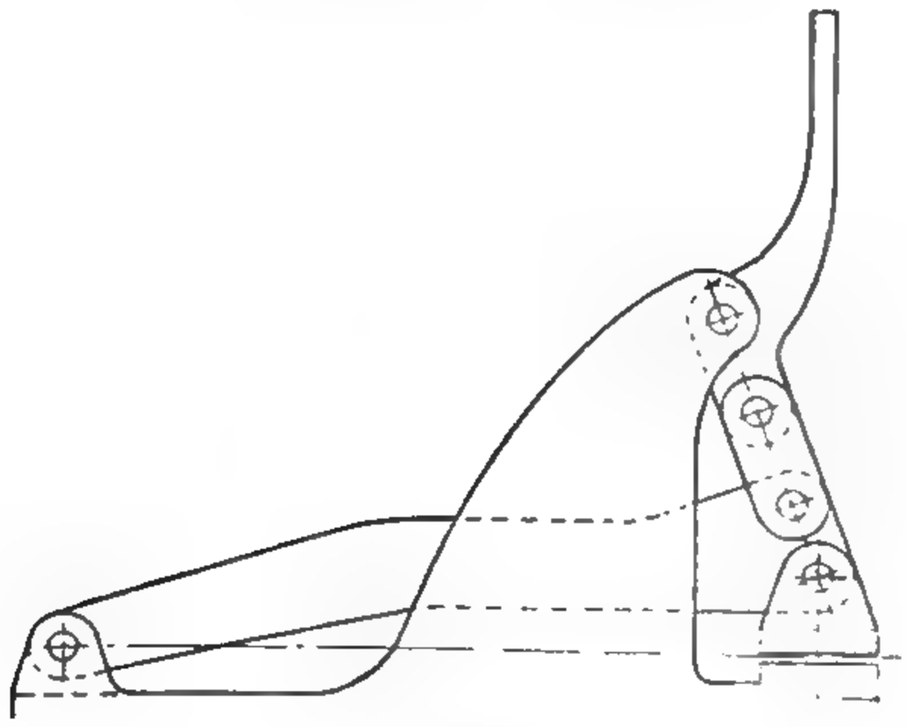
D. Vertical, air-toggle operated.



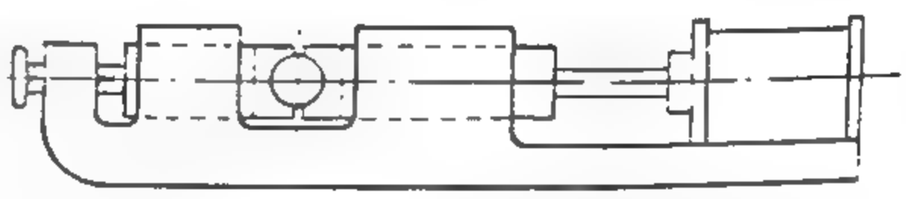
B. Vertical, air-cam operated.



E. Horizontal, hand-toggle operated.



C. Vertical, hand-toggle operated.



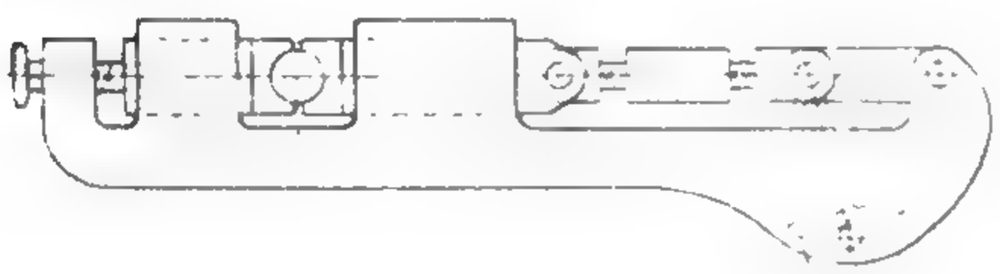
F. Horizontal, direct-air operated.

Fig. 16.—Several Typical

to a wide variety of work, such as wide strips or sheets and other special applications. Since this fixture may have considerable height, it cannot be used where this height may interfere with the work, such as in welding closed bands.

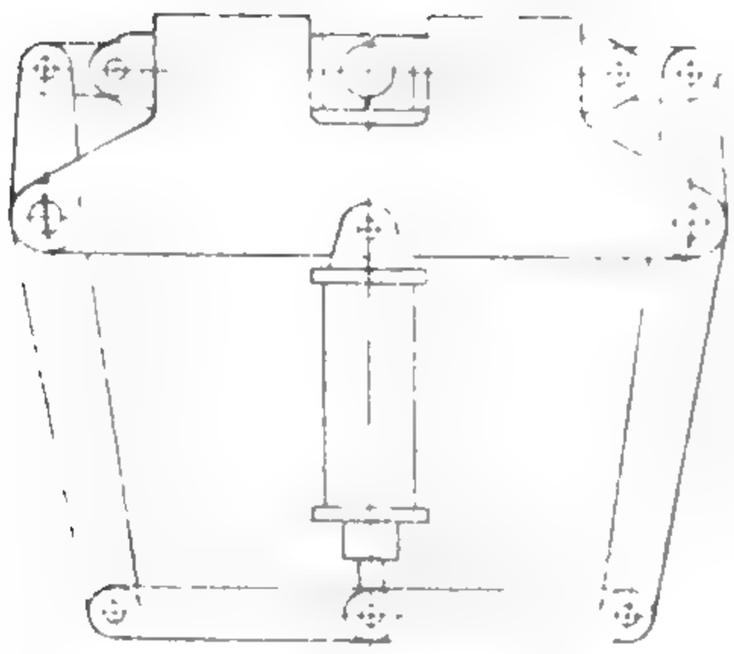
(*b*) Horizontal: This type of fixture has a horizontal action, and its principal advantage lies in the fact that usually both front and back dies carry current. For this reason, it is generally desirable to use this type of fixture for tubing, also large round bars and other large concentrated sections. Another advantage lies in the ease with which alignment of the work-pieces may be obtained. The fixtures are usually provided with screw or wedge adjustments which permit the work to be aligned both vertically and horizontally.

Type of Operation.—Most styles and types of fixture can be arranged for hand, air or hydraulic operation, and the selection of the type of operation depends on the size of fixture, clamping pressures required and other considerations. Various mechanical motions are employed to intensify the force from the power source, as (*a*) simple lever, (*b*) simple or compound toggle, (*c*) cams, (*d*) eccentric, etc.



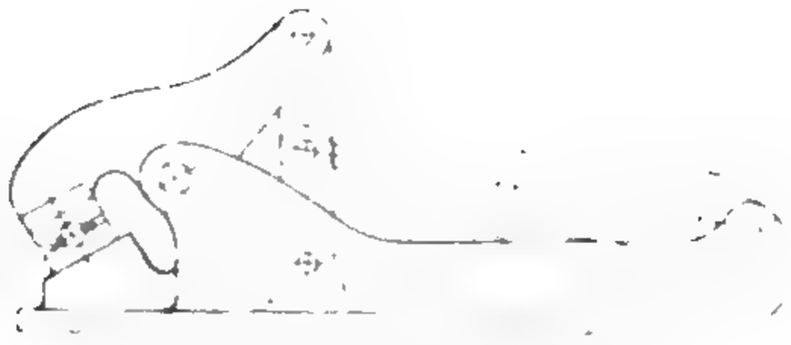
G. Horizontal, air-toggle operated.

J. Alligator, air lever operated.

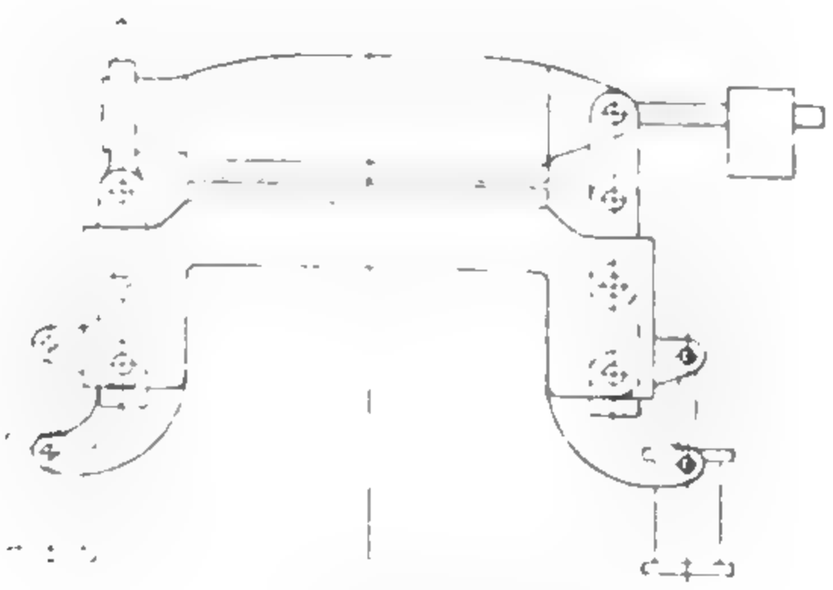


H. Horizontal, air toggle equalizing.

K. Alligator, air-toggle operated.



I. Alligator, air-toggle operated.



L. Vertical, double air-toggle oeprated with front gate.

Flash-Welding Clamping Fixtures

Small machines (50 kva. and under) usually have the clamping fixtures built integrally with the platens, while the larger machines are generally of flat top construction with bolted fixtures.

Backups and Locators.—Large flat sheets, rings and bands and other sections must be clamped in the dies with sufficient pressure to prevent slippage during upset. This may require extremely large and heavy fixtures. However, if the work is of such a nature that it can be backed up outside the fixture, then only sufficient clamping pressure to insure good electrical contact is necessary and the fixture may be considerably lighter. These backups are usually adjustable to accommodate the range of work length required and must be sufficiently sturdy to withstand the upset force without yielding or deflecting.

Various types of locators may be required for holding the work in proper position in the dies. These may be simple stops or guide bars, and again, may be more elaborate to hold bars exactly concentric and parallel.

Controls

Controls for flash- and upset-welding machines are quite simple and consist principally of a contactor for applying the welding current and a means for closing and opening it.

Contactors.—Magnetic contactors are best suited to most installations, and are the most commonly used. On hand-operated machines, they are closed by push button or foot switch and opened also by hand or by a limit switch mounted on the platen and connected in series with the push button. On motor-driven or automatic hydraulic machines, they are closed and opened by means of a limit switch operated by means of an adjustable cam.

Ignitron or tube contactors are also used. These give satisfactory service, but it is also usually necessary to use a load resistor with 100% duty cycle rating.

Auxiliary Controls

For welding certain types of steel, usually air-hardenable types, it is sometimes necessary or desirable to apply a postheat or normalizing operation immediately after welding. To accomplish this, it must be possible to unclamp the work, reclamp it with greater die opening and again apply the current, usually of a lower value. This requires a second contactor connected to a different tap on the transformer. This postheating may be controlled entirely by hand or by means of a timer. If a tube contactor is used, a phase-shift heat control with two control stations may be used, one for welding and one for postheating.

RESISTANCE WELDING ELECTRODES

Electrodes, whether for spot welding, seam welding or flash welding, all perform the same function. They conduct the welding current to the work. Some, as in spot welding, conduct the current and provide the welding force. Others, as in butt welding, conduct the current but provide welding force in a different plane. Spot-welding and seam-welding electrodes have a very high current density at the point of contact with the work. On the other hand, projection-welding and upset-welding electrodes may have a relatively low current density.

It is not possible to lay down a set of rules for proper electrode selection for all applications. However, by an understanding of the governing factors, a reasonably close approximation can be made, with the final selection usually being worked out experimentally on a production basis. Often the best material for a given job may be determined by the maintenance policy of the individual plant.

Electrode Material Standards

The physical properties required for electrodes vary with the types of materials being welded. Recommended uses of RWMA standard alloys, based on use with proper equipment, are as follows:

Group A—Copper Base Alloys

Class 1.—Class 1 alloy is a superior substitute for pure copper as an electrode material and is recommended as a general-purpose material for resistance welding applications. It may be used for spot-welding electrodes, seam-welding electrodes, seam-welding shafts, flash- and upset-welding dies, projection-welding dies and fixtures.

It is specifically recommended, because of its high electrical and thermal conduc-

tivity, for spot-welding aluminum alloys, magnesium alloys, coated materials (terne plate, tin plate, galvanized iron, cadmium plate), brass and bronze. Class 1 alloy is not used in cast form.

Class 2.—Class 2 alloy is a superior resistance-welding electrode material specifically recommended for high level production spot and seam welding of clean mild steel, low-alloy steels, stainless steels, low-conductivity brasses and bronzes, nickel-silver, nickel and nickel alloys including Monel. It is suitable for projection-welding dies, seam-welding shafts and bearings, flash- and upset-welding dies and current-carrying structural members.

It is available as high-strength and high-electrical conductivity castings for such use as gun welding arms, welding platens and secondary circuit structural members. The Class 2 alloy is heat-treatable.

Class 3.—Class 3 alloy is specifically recommended for projection-welding dies, flash- and upset-welding dies, current carrying shafts and bushings. As castings, Class 3 alloy (having higher strength than Class 2) is recommended for highly stressed, structural, current-carrying machine members and heavy duty offset electrode holders.

Class 3 alloy electrodes are not generally recommended for spot welding but may be used advantageously for spot welding steels having high electrical resistance, such as stainless steels. The Class 3 alloy is heat-treatable.

Group B—Copper-Tungsten Alloys

Class 10.—Class 10 is recommended as facings or inserts for projection-welding electrodes and flash- and upset-welding dies where high electrical conductivity is desirable and a degree of malleability is necessary.

Class 11.—Class 11 (a harder material than Class 10) is recommended as facings and inserts for flash- and upset-welding dies and general-purpose projection-welding electrodes. It may also be used as seam-welding bearing inserts and facings for electro-forming or electro-forging dies. It is recommended for spot welding of steels having high resistance, such as stainless steel.

Class 12.—Class 12 material is specifically recommended for heavy-duty projection-welding electrodes and for die facings in electro-forming and electro-forging applications. It is suitable as die material for electrical upsetting of rivets and studs.

Class 13.—Class 13 material is recommended principally for welding or brazing nonferrous metals having relatively high electrical conductivity.

Cross-wire welding of copper and brass wires and welding of copper wire braid to brass and bronze terminals are typical applications. Generally, special setups and procedures are required for this type of work.

Types of Alloy

Each class of electrode material has been found most suitable for a particular group of applications. There is a considerable difference in the electrical conductivities of the materials, because experience has indicated that high electrical conductivity, however desirable it may be, is often not so important to the economy of the operation as long life and long service between dressings. Increased wear resistance (high hardness and proportional limit) is accompanied by lower conductivity. This suggests selection of electrode material in the classification which has the least conductivity that will produce good welds for a given application, so as to take advantage of the greater wearing properties. It should be noted that if the conductivity is too low, sticking or alloying of the electrode face is experienced, particularly in spot and seam welding.

Hardness at room temperature (usually accepted as a good index of wear resistance) is not necessarily a reliable guide to expectancy of life in electrode material, because it does not indicate a definite degree of resistance to deformation, or *mushrooming*. A preferred method of measuring the resistance to deformation is to determine its proportional limit.

Since most metals and their alloys tend to undergo a decrease in mechanical properties at elevated temperatures, a minimum heating of the electrode material is desirable. Figure 17 shows temperature-hardness curves for various electrode materials.

Class 1 electrode materials owe their mechanical properties to composition and cold work, and will withstand deformation at considerably higher temperatures than hardened pure copper.

Class 2 electrode materials derive their

properties from a combination of composition, cold work and heat treatment. Class 3 materials are heat treated and may or may not be cold worked. These two classes of material will operate satisfactorily at higher temperatures than Class 1 alloys which are not heat treated.

Group B electrode materials are not solid solution alloys but pressed and sintered mixtures of tungsten and copper. They are recommended for application where extremely high resistance to deformation is of more importance than electrical conductivity.

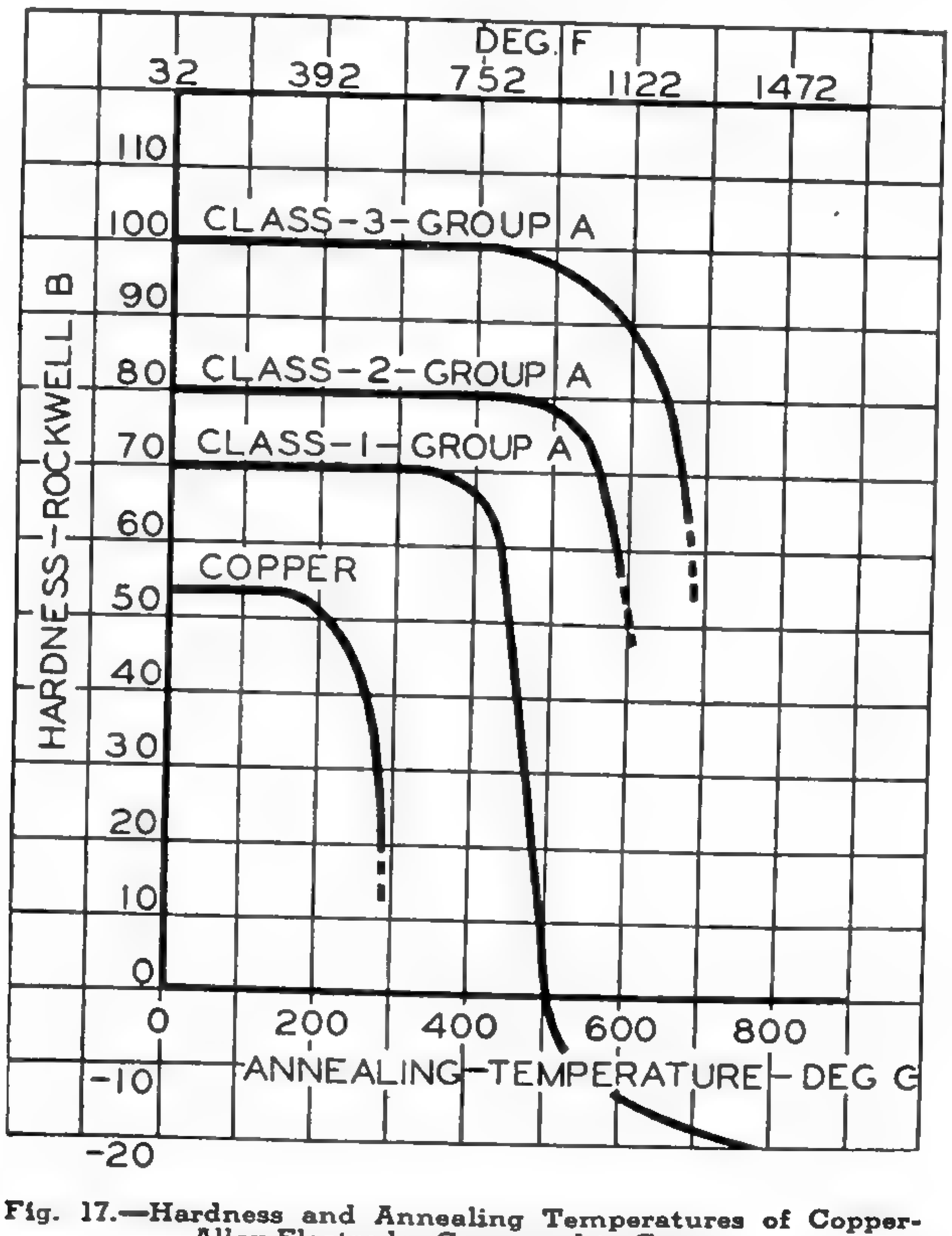


Fig. 17.—Hardness and Annealing Temperatures of Copper-Alloy Electrodes Compared to Copper

Spot-Welding Electrodes

The spot-welding electrode is in direct contact with the work at the weld, with a relatively small area of contact, and the possibility of metal pickup or sticking of the electrode is a primary consideration. The proper alloy should be selected on the basis of adequate electrical conductivity of the electrode and the surface condition, chemical composition and other factors affecting the weldability of the metal being fabricated. Spot-welding electrodes should be easily removable from their holders to facilitate replacement for remachining or for substitution of a new electrode. There are several types of mountings and means of clamping or securing electrodes in holders. The RWMA standard mounting is that of a No. 1, No. 2 or No. 3 Morse taper shank on the electrode, fitting into a corresponding socket in the electrode holder. Figure 18 illustrates RWMA standard electrode holders.

Electrode Design.—Many factors affect the design of electrodes, such as accessibility of the weld area, composition and thickness of the parts being welded, finished surface requirements, etc.

Principal considerations in electrode de-

sign are: Electrode material; electrode shape and dimensions; and provision for cooling.

The ideal shape is the straight electrode. This should always be used when the accessibility of the weld area makes it possible, because the load on the electrode is always a compression load, electrode tip wear is more nearly uniform and maintenance is lowest. For the welding of joints that are not readily accessible for welding with a straight electrode, many hundreds of electrode shapes have been devised.

Electrode Maintenance.—Good maintenance of electrodes is necessary for the production of good consistent welds. Allowing electrode deterioration to proceed until welds become unsatisfactory is poor practice. Abnormal increases in the size of contact area will impair weld strength and quality. If a $^1/_4$-in. diam. electrode face is allowed to increase to $^5/_{16}$ in. by

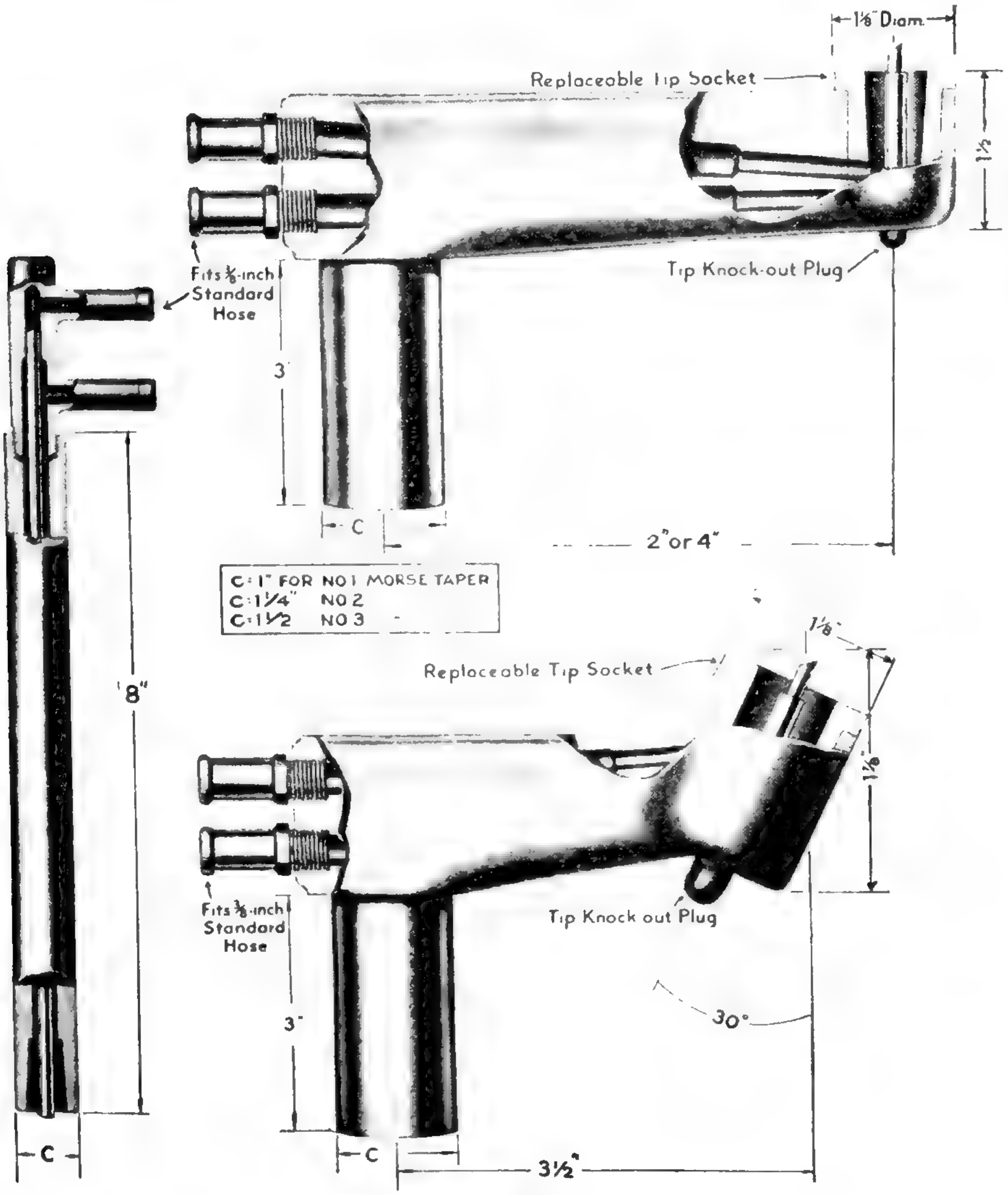


Fig. 18.—RWMA Standard Straight and Offset Holders

mushrooming, the contact area is increased 50%, with a corresponding decrease in current density. Unless this is compensated for by an increase in welding current, the result will be weak welds or no welds at all.

Another danger sign is the production of poorly shaped spots, which may be caused by:

(*a*) Non-circular outline of tip face.
(*b*) Use of too large a flat face on the tip.
(*c*) Use of flat tip with blunt and irregular edge.
(*d*) Concavity or convexity of the tip.
(*e*) Failure to maintain tips parallel to the work.
(*f*) Misalignment of electrodes.

Correct alignment is relatively easy when stationary machines are used, but with gun-type machines lack of alignment is common, and will be more or less serious depending on the ease of manipulating the equipment for the particular application. Therefore, it is to be expected that the same electrode will have longer life between dressings on positioned work (stationary machines) than on non-positioned work (gun welders).

Since mushrooming is largely the result of annealing, it follows that to keep the electrodes properly maintained, they must be effectively cooled. The presence of water does not necessarily assure cooling. It must be circulating water, free from dead spots which produce steam pockets. Provision has been made in the recommended holders for adjustable cooling tubes so that circulation as close to the electrode face as possible is assured. This is an important consideration too often neglected.

The shape and finish of the electrode face are of paramount importance. Finishes and shapes made by hand filing in the machine are not conducive to either good welds or long life. Hand- or power-operated electrode milling cutters are available, as well as hand-operated contour polishing devices.

For best maintenance, it is recommended that knock-out type holders be used and that a large supply of electrodes be kept available. Worn electrodes should be removed and remachined in lots in a lathe, using the special tools which are available for this purpose.

Compounds must not be used to prevent water leaks between the electrodes and holders. The connection of the holder to the machine arm should be firm and free from dirt, oil or oxide.

Seam-Welding Electrodes

Seam-welding electrodes are generally in the form of wheels and are sometimes referred to as seam-welding wheels. An exception to this is when a flat anvil or mandrel is used on one side with a wheel on the other. In either case, however, the actual application is essentially the same as spot welding and the electrode materials are generally the same. Only the shape is changed.

Seam-welding wheels are of two types, one for knurl or friction-roll driven machines, the other for gear or idling applications. The essential difference between the two types is their thickness and welding face contour or shape. Knurl or friction roll driven wheels must fit the knurl contour or shape. Knurl-driven wheels are used principally on coated stock, because during the welding operation, the coating sticks or alloys to the wheel face. The knurling on the drive roll breaks up this coating. The friction drive roll is the same as the knurled roll but with the knurling omitted. Both, however, are so constructed as to continually dress the sides of the wheel, thus preventing mushrooming and maintaining uniform face width. Gear driven or idling wheels are sometimes provided with an idling knurling tool to perform this same function.

Projection-Welding Electrodes

For projection welding, it is necessary to maintain the opposing faces of the dies parallel. If the dies wear non-uniformly, or if they develop cavities, non-uniform pressures and current densities will result, thereby producing non-uniform and defective welds.

Projection-welding dies have flat surfaces with larger contacting area than spot-welding electrodes. The deterioration of the dies is not so great as in the case of spot welding since the heat and wear are distributed over larger areas. However, since most projection-welding dies are produced to accurate dimensions and involve accurate machine work, the use of the best possible materials results in the lowest operating cost. Due to the larger contact area the dies may be

made from materials having relatively lower electrical conductivity than those employed in spot welding. Thus advantage is taken of the superior wear resistance of the higher strength alloys such as Class 3 and Group B alloys.

Some projection-welding dies are quite simple, others are more complicated, depending on the nature of the job. The simplest construction provides the die and die holder in one piece, bolted or clamped directly to the machine platens. Others are made up in sets with removable or replaceable inserts. The selection of materials for one-piece dies depends on the nature of the job and the production requirements. For the less exacting jobs, solid dies of RWMA Class 2 or Class 3 alloys give good results. For higher production, and especially where lost time due to die maintenance is an important factor, the bases may be of Class 2 or 3 alloy with brazed inserts or facings of Class 11 or 12 material. If the projections are close together, the entire facing may be one piece, but if they are sufficiently separated, individual pieces are desirable.

Projection-welding dies frequently have gages, clips, locators, etc., attached to them. In the use of such devices, care must be exercised to prevent them from carrying current with resultant pitting.

Installation and Maintenance.—The success of projection-welding operations in production depends largely on three factors as far as electrodes are concerned:

1. Proper selection of materials.
2. Proper installation.
3. Proper maintenance.

Assuming that the dies are of correct design and construction, the installation is next in importance. First, the platens of the machine should be carefully checked to make sure that they are level and at right angles to the motion of the ram. The platens must also be smooth and clean—free from dirt, nicks, pitmarks, etc. If these conditions are not met, the platens should be removed and machined before any attempt is made to install the dies. The check for parallelism of the platens must be made under normal operating pressures. This can best be done by inserting a steel block with known smooth and parallel faces between the platens and checking with feelers. Another good check is to place tissue paper under the corners, then feel for looseness. Prussian blue or carbon paper may be placed on the block to register on the paper. However, *never* allow Prussian blue to get on the platens, as it is difficult to remove and can start corrosion of the platens. Next, check the base of the die blocks. They must be clean, smooth, level and free from burrs and nicks; if not, a machine cut should be taken.

The dies can now be installed in the machine. Most machines have tee-slots in the two platens cut at right angles to one another to permit universal alignment of the dies. When they are properly lined up, they should be bolted down securely. With the work in place, the ram or knee (whichever is adjustable) should be adjusted for the proper stroke, making the necessary allowance for upset of the projections.

If the faces of the projections are all in one plane, and if they have been checked for uniform height, it now can be assumed that the set-up is ready for trial welds. If the trial indicates non-uniformity of current or pressure, before attempting to correct the dies, make sure that the trouble does not lie somewhere else, as (*a*) shunting of current through locators, (*b*) unequal distribution of current caused by some projections being considerably closer to the transformer than others; (*c*) too much play in the welding head; (*d*) too much deflection in the knee.

The use of shims between die components or between dies and platens is to be avoided as much as possible, but this is generally regarded as a necessary evil. If the correct alignment cannot be obtained otherwise, there is no other recourse. When shims must be used, they should be only of high-grade soft copper sheet and with sufficient area to carry the necessary current. Also, they must be absolutely clean.

If the projections are located on curved or angle surfaces, accurate templets should be provided for checking the dies, keeping in mind that the final proof of the setup is the actual weld. Also, when welding curved surfaces, or two or more pieces to other parts, difficulties may be encountered on account of the manufacturing tolerances of the metal thicknesses involved. There is no cure for this condition except to provide for it in the design of the parts and arrangement of projections.

Flash- and Upset-Welding Dies

Flash- and upset-welding dies present a somewhat different problem from other forms of resistance-welding electrodes. They do not come in direct contact with the weld, but are often subject to higher unit pressures. They do, however, conduct current to the pieces being welded. Also, unlike other types of electrodes, die materials selected for various applications do not depend upon the material being welded, but the selection is often governed by the physical shape of the work-pieces.

Since the current carried per unit of contact area is relatively low, the conductivity of the die material is not as important. The important factor is its compressive strength. For welding sheets, tubes, bars, rods, etc., with smooth surfaces, the electrode material should be very hard. If the surfaces are pitted, scaly or otherwise uneven, the material should not be so hard, thus permitting the electrodes to partially adjust themselves to the work-pieces. For forgings and castings, still softer materials should be used. It will be noted that the material being welded (stainless steel, low-carbon steel, aluminum, brass, etc.) has practically no effect on the die material. However, nonferrous metals require good current distribution in the dies, so that for these, materials having higher conductivities are desirable.

There are no standards for the design of upset welding dies, due to the variable nature of the work parts. Dies, like machines, must be suitable for all conceivable shapes, forms, etc., that can be welded. Dies for flat-top machines are bolted or clamped either directly to the machine platens, or held in die holders which are, in turn, bolted or clamped to the platens. When dies are mounted in holders, they are usually not water cooled, but the holders are.

Flat-top machines usually introduce welding current to the work through the lower die only, in which case the upper die may be made of tool steel, Stellite-faced steel or aluminum bronze. Where conditions permit, these upper dies are serrated to provide greater gripping action to resist upset forces.

Clamping fixtures designed for welding bar or tubular stock are often designed to accommodate inserts for handling various diameters. This construction greatly reduces die costs when a considerable number of sizes are involved, as for example, when separate dies must be used for drills in each $^1/_{16}$-in. diam. and sometimes in 32nds. The dies in all cases should fit the work exactly.

For clamping forgings and castings, the dies should be properly routed out to follow the contours. While it is difficult to give specific instructions, it is important that a good fit be made on contact surfaces adjacent to the weld, with the remaining contact surface sufficiently good to maintain alignment of the parts being welded.

Most horizontal fixtures are provided with universal die adjustments for securing alignment. Some machines are also provided with vertical adjustment on one or both of the lower dies. When no adjustments are provided, it is necessary to shim one of the dies. The use of shims should be avoided as much as possible, but when it is necessary, certain precautions should be followed:

(*a*) Use as few shims as possible. That is, use one shim 0.010-in. thick rather than two 0.005-in. thick. This reduces the number of contact surfaces.

(*b*) Make sure all shims are clean and have no ragged or folded edges.

(*c*) It should not be necessary to shim both sides.

(*d*) All surfaces in contact with the shims should be clean.

(*e*) Keep alert for signs of corrosion. This is manifest first by excessive heating of the dies. If any of the contacting surfaces become discolored or black, do not allow them to get worse. Clean them immediately.

(*f*) Do not try to file any of the contacting surfaces. They should be accurately machined.

(*g*) Be particularly careful of the platen-contacting surfaces. Machine operations on these are very expensive.

With proper care, electrode maintenance on flash welding machines should be a minor problem.

RESISTANCE WELDING CONTROLS

The proper functioning of any resistance-welding machine depends in a large measure on its controls. These controls provide two principal functions:

initiating and stopping the flow of current, and controlling the magnitude of current—and they fall into three general groups:

1. Contactors.
2. Sequencing and timing devices.
3. Accessory devices.

These control devices may be applied to a machine as individual units, or they may be grouped into a single enclosure.

Welding Contactors

A contactor is defined as a device for repeatedly establishing and interrupting an electric power circuit. In the case of the welding contactor, this power circuit is the primary circuit of the welding transformer. There are three basic types of welding contactor:

1. Magnetic contactors (ordinary or synchronously interrupting).
2. Electronic contactors (with ignitrons or thyratrons).
3. Mechanical contactors (motor- or foot-pedal operated).

Specific jobs performed on any machine will vary considerably. It is therefore recommended that the welding contactor size be selected to handle the maximum input which the machine is capable of taking from the power line under welding conditions with the current regulator at the highest tap. This input may be expressed as the maximum kva. demand. The input current under these conditions is expressed as the maximum demand rms. amperes.

Magnetic Contactors.—A magnetic contactor consists of current-carrying contact members actuated by an electromagnet. When electrically energized, the magnet supplies the closing force which brings the contacts together to establish the power circuit to the primary of the welding transformer. When de-energized, the magnetic pull disappears and the contacts are opened by spring pressure and gravity.

Types available are:

1. Single-pole contactors to break one side of the single-phase power line.
2. Double-pole contactors to break both sides of the single-phase power line. (Can be connected with poles in series or parallel on one side of the line.)
3. Synchronously interrupting magnetic contactors. (Usually single-pole.)

Any of the above three types of contactor may be used when applied within its respective current and duty cycle ratings.

Synchronously interrupted magnetic contactors open the power circuit at an instant when the alternating current wave approaches zero. This opening at zero current means that virtually no arcing results. Elimination of the arcing prolongs contact tip life and permits worthwhile increases in ratings as compared to the conventional types.

In general, standard magnetic contactors intended for industrial service are not satisfactory for resistance welding applications. Instead, construction involving nearly frictionless bearings, light moving parts, short contact gaps, strong contact spring pressure, large cross-section current-carrying parts, special magnet structures and unusual arc-suppressing means have been found necessary.

Magnetic contactors are classified by six size numbers with nominal and maximum demand ampere ratings as given in the following table:

NEMA Size Number	Nominal Rating, Amp.	Maximum Demand During Welding, Rms. Amp.
0W	50	200
1W	100	400
2W	150	600
3W	300	1200
4W	600	2400
5W	900	3600

The nominal rating represents the load which can be carried continuously without exceeding the temperature rise on which the rating is based. It has little meaning except for comparison purposes, since resistance welding service is intermittent in nature.

Contactors for any given machine or application are determined by the maximum demand and the duty cycle. For most applications, the duty cycle can be neglected and the selection made by maximum demand only. If any doubt exists, the manufacturer's recommendation should be obtained.

Electronic Contactors.—Electronic contactors are electronic switching devices which control the current to the primary of the welding transformer. The primary current is carried in its entirety by controlled gaseous discharge tubes called ignitrons. The ignitron contactor is especially valuable for those applications requiring an extremely high number of

welding operations per minute or which require extremely high welding currents. Either of these conditions imposes very severe duty on mechanical contactors.

Standard sizes of electronic welding contactors mount two inversely connected tubes to make and break one line of a single-phase welding system.

Figure 19 shows a typical diagram of an ignitron contactor connected to a machine. The contactor consists of two ignitron tubes connected in inverse parallel so that one of the tubes carries the positive half-cycle of welding current and the other carries the negative half-cycle of welding current. These two tubes together act as a single-pole electronic switch to control the flow of current in the primary of the welding transformer.

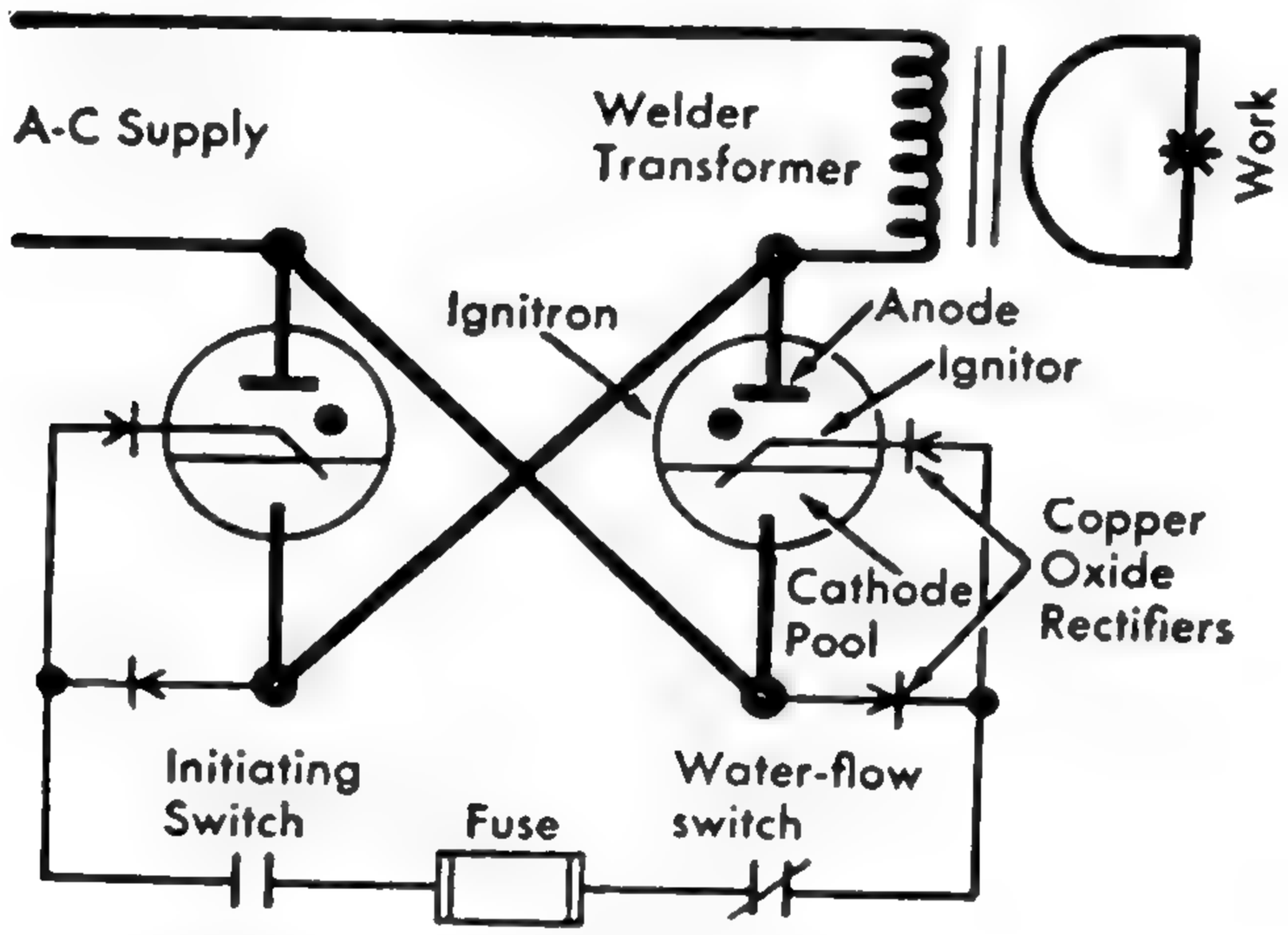


Fig. 19.—Schematic Diagram of Tube Contactor Power and Control Circuits

An ignitron tube is constructed as shown in Fig. 20. It consists of a steel vacuum-tight container with a pool of mercury in the bottom to serve as a cathode, a graphite anode at the top supported by an insulating glass bushing through which the power lead is brought to the anode and an ignitor which is used to start the flow of current in the tube.

Most ignitrons are water-cooled and have a water jacket made of stainless steel to prevent corrosion.

The ignitron is a rectifier since current will flow only from the graphite anode to the mercury pool cathode. Hence, two tubes are required to conduct alternating current.

The ignitor will cause the ignitron to begin conducting current if a sufficient pulse of current is passed from the ignitor to the mercury pool. The ignitron will not stop conducting current until the current has been reduced to zero which occurs at the end of each half cycle of alternating current. It is then seen that the ignitor must start conduction for each individual half-cycle during which current flow is desired.

The control circuit of the tube contactor is very simple and is shown in light lines in Fig. 19. The copper oxide rectifiers are used to allow current flow from the ignitor to the mercury pool only. A control circuit fuse is provided for protection of the ignitors and isolation of the remainder of the control circuit from the power circuit. A water-flow relay is provided in the contactor to prevent operation of the contactor with insufficient cooling water in the jackets.

The tube contactor energizes the welding circuit when the control circuit is closed. This control circuit requires no additional voltage, its potential being obtained from the power circuit. Each ignitron is fired for each conducting half-cycle by its ignitor which is energized through the control circuit whenever the control circuit is closed by the timer.

A surge suppressor resistor is connected across the primary of the welding transformer, to absorb the magnetic

energy which may be left in the welding transformer at the end of the weld.

The effect of duty cycle on the selection of ignitron tube sizes is much more critical than for magnetic contactors. This is particularly true since duty cycle averaging time is a matter of a few seconds, depending on the tube size. Tube manufacturers' rating charts should be carefully followed in the application of these tubes.

Mechanical Contactors.—Mechanical contactors may be either single-pole or double-pole, and consist merely of contacts actuated by motor-driven cams or eccentrics. They are sometimes driven directly by the welding machine itself. Mechanically-operated contactors have largely been superseded by other types because they do not have the flexibility necessary for modern requirements.

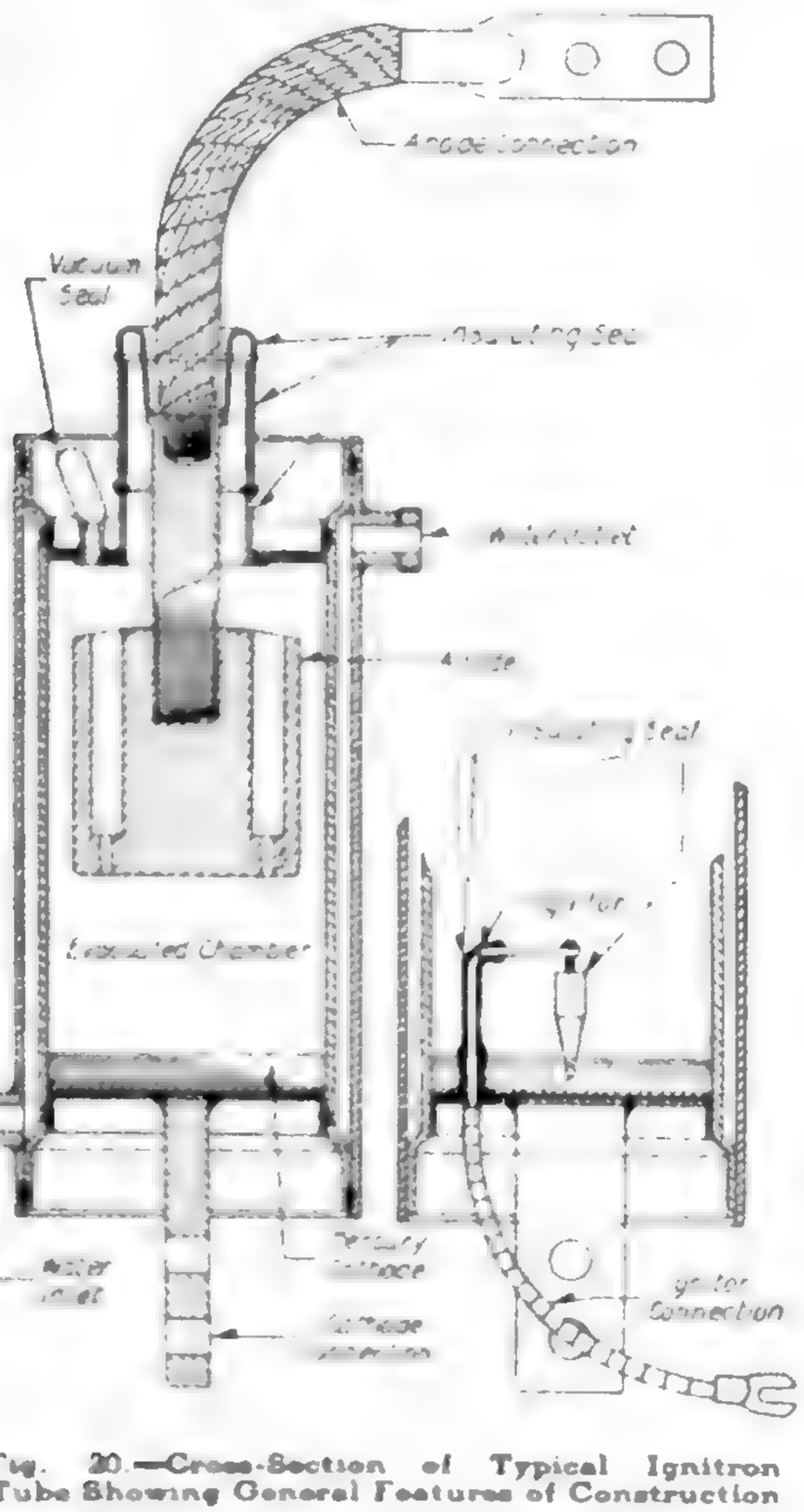


Fig. 20.—Cross-Section of Typical Ignitron Tube Showing General Features of Construction

Ignitron tubes require a minimum load current to insure satisfactory operation. If the primary current to the machine is liable to be less than 40 amp., an auxiliary load resistor should be used. This resistor is permanently connected in parallel with the machine terminals and merely provides the required minimum tube loading

Timing and Sequence Controls

Modern high-speed welding requires controls to sequence the operation of air and hydraulic machines, and also to accurately time the application of current.

Weld timing devices are classified in two general types—non-synchronous and

synchronous precision. There are several kinds of each type.

Non-Synchronous Types.—A non-synchronous timer is one which starts and stops the flow of welding current at *random* points with respect to the line current wave form. Closing and opening the welding contactor at random points on the wave form result in a variable of time as well as a variable in current input to the machine. The time variable will be at least plus or minus $^1/_2$ cycle and sometimes more. On welds of 20 cycles duration or more, this results in a low percentage of variation and can usually be neglected. If the welding time is below 10 cycles, this percentage of variation becomes somewhat greater, usually requiring synchronous precision timing. From 10 to 20 cycles, the nature and quality of the work will determine the type of timing.

Several types of mechanisms are employed to obtain timing periods. As outlined later, these timing periods also include, in addition to the weld time, sequencing periods for completely controlling the operation of the machine. These timing mechanisms are:

Electromagnetic. Timing by the electromagnetic or induction principle is based upon the interval required to discharge energy stored in the field of a specially designed magnet. A direct-current charging source, usually a copper oxide rectifier, supplies a charging current for the system, and the energy stored in the field of the magnet coil is discharged through a paralleled resistance when the charging circuit is interrupted. The time required for the magnet to discharge is inversely proportional to the value of resistance connected in parallel with the coil—infinite resistance providing the shortest timing period possible with the design of mechanism used.

Electrostatic. The electrostatic principle is based upon the constant time interval required to either charge or discharge a condenser of a given size, assuming a fixed charging current and a specified value of resistance in the charge or discharge path.

Most modern electronic timers are of this type.

Pneumatic. A pneumatic timer is a mechanical device, consisting of electrical contacts actuated by delay mechcanisms involving the transfer of a small volume of filtered air from one chamber to another. A regulated orifice determines the speed of transfer of air, and therefore the length of the timing period. A needle valve with adjusting knob is used to set the timing period. The time setting is usually indicated in cycles on a calibrated dial geared to the needle valve.

Motor. Motors having a constant operating speed can be applied for timing purposes. Cam-operated contacts close and open the circuit to the operating coil of the welding contactor. A clutch is sometimes used to engage and disengage the cam shaft, allowing the motor to run continuously. Occasionally the cam shaft is directly connected to the motor which is then started and stopped at the beginning and end of each timing period.

Synchronous Precision Timers.—A synchronous precision timer provides an accurate timing period and both closes and opens the primary circuit of the welding transformer at precisely the same point with respect to power-circuit voltage in making each weld. Thus the current wave form is consistent and the energy delivered to the welding transformer is the same for consecutive operations.

The control of the point at which the the power circuit is closed is vital for precise results. If the highly inductive circuit, characteristic of a welding transformer, connected to the power circuit at a point corresponding to zero current (if current were flowing), then no transient will occur and the current during the first half-cycle will be practically the same as the steady state current throughout the weld. On the other hand, when the power circuit is closed at the time the current would be maximum (if current were flowing), a transient primary current results. Its peaks are greater in magnitude than those corresponding to normal or steady state currents. The transients in the secondary winding of the transformer are not so great but they are sufficient to materially affect the energy delivered to the weld.

Figure 21 shows two waves of a.c. welding current, one of which is the wave type obtained with a synchronous timer for all welds and the other is the type which occurs to a greater or lesser degree in a random manner when using a non-synchronous timer.

The nature of the transient resulting from any particular closing of the pri-

mary current depends upon the magnetic condition of the transformer core, the connected load and the point on the voltage wave at which the circuit happens to be completed. Since the magnetic condition of the core depends upon the magnitude and direction of the last preceding current flowing in the transformer winding, it is evident that the point of opening as well as closing of the power circuit must be controlled if uniform results are to be obtained.

For minimum inrush transient currents, the initial half-cycle of current must be in the direction opposite to that last flowing and the circuit must be closed at the point where the current would be passing through zero under steady state conditions—the exact point being determined by the power factor of the circuit, since that determines the instant the current is zero, if flowing.

Synchronous controls, both spot- and seam-welding types, consist of two principal elements, contactor and timer. The contactor consists of two ignitron tubes connected in inverse parallel exactly like the ignitron contactor except that the copper oxide rectifiers are omitted. The ignitrons are fired or controlled by thyratron tubes, which are, in turn, controlled by a timing circuit. Space does not permit more details on these controls. For more information, refer to *RWMA Resistance Welding Manual,* or other technical books on the subject, some of which are listed in the bibliography at the end of this chapter.

In addition to the timer and contactor elements, most synchronous controls are also provided with *heat control,* discussed later on in this chapter.

Sequence and Sequence-Weld Timers

The four basic steps required for the most common type of complete spot- or projection-welding machine cycle are (1) time for the electrodes to close and develop pressure on the work (Squeeze Time), (2) initiate and time the current flow to welding transformer primary (Weld Time), (3) hold the electrodes together a preset time after weld current has been interrupted, while the weld solidifies (Hold Time) and (4) open the electrodes to allow the work to be moved into a position for the next weld (Off Time).

The weld timing may be either non-synchronous or synchronous. If the weld timing is non-synchronous, the time function may be built into and be an integral part of the sequence control. Such units are called *sequence-weld timers.* When weld timing is accomplished by

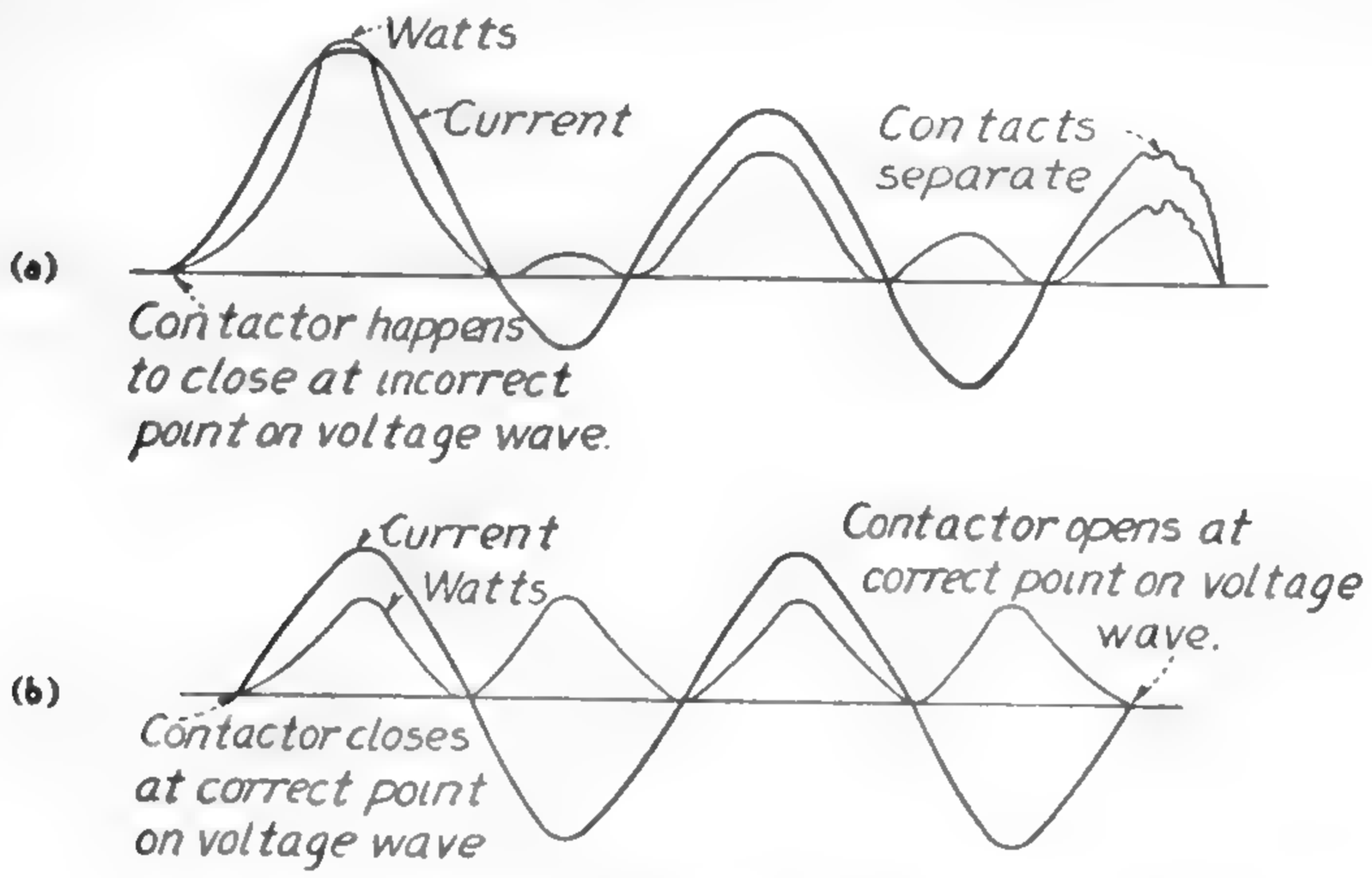


Fig. 21.—Curves Showing Difference in Current and Watt Waves When Circuit is Closed Synchronously and Non-synchronously

(*a*) Shows closure of the circuit at the incorrect point and resultant decaying transient. The opening is also non-synchronous.

(*b*) Shows synchronous opening and closing of the circuit at the point of zero current corresponding to minimum transient.

synchronous control and the sequence of welding machine operations is timed, the units are called *sequence timers.*

Certain resistance welding machines use manual or motor-operated electrodes geared to a camshaft which initiates the weld timer. In most installations of this type a single function weld timer is used to time only the duration of welding current.

Pulsation welding timers provide for a number of welding impulses, the duration of each of which is controlled, as well as the time interval between impulses. This total time is known as *weld interval.*

is governed by a cam or other overall device.

NEMA Type 3B—This is the most popular timer used today, and controls overall sequencing of the welding machine—squeeze, weld, hold and off periods.

NEMA Type 5B—This is used for pulsation welding, and in place of the weld time, on the 3B device, provides control of weld interval, heat and cool times.

NEMA Type 7B—This is a sequencing panel for use with a synchronous timer, and provides the same functions as the 3B.

NEMA Type 9B—A sequencing panel

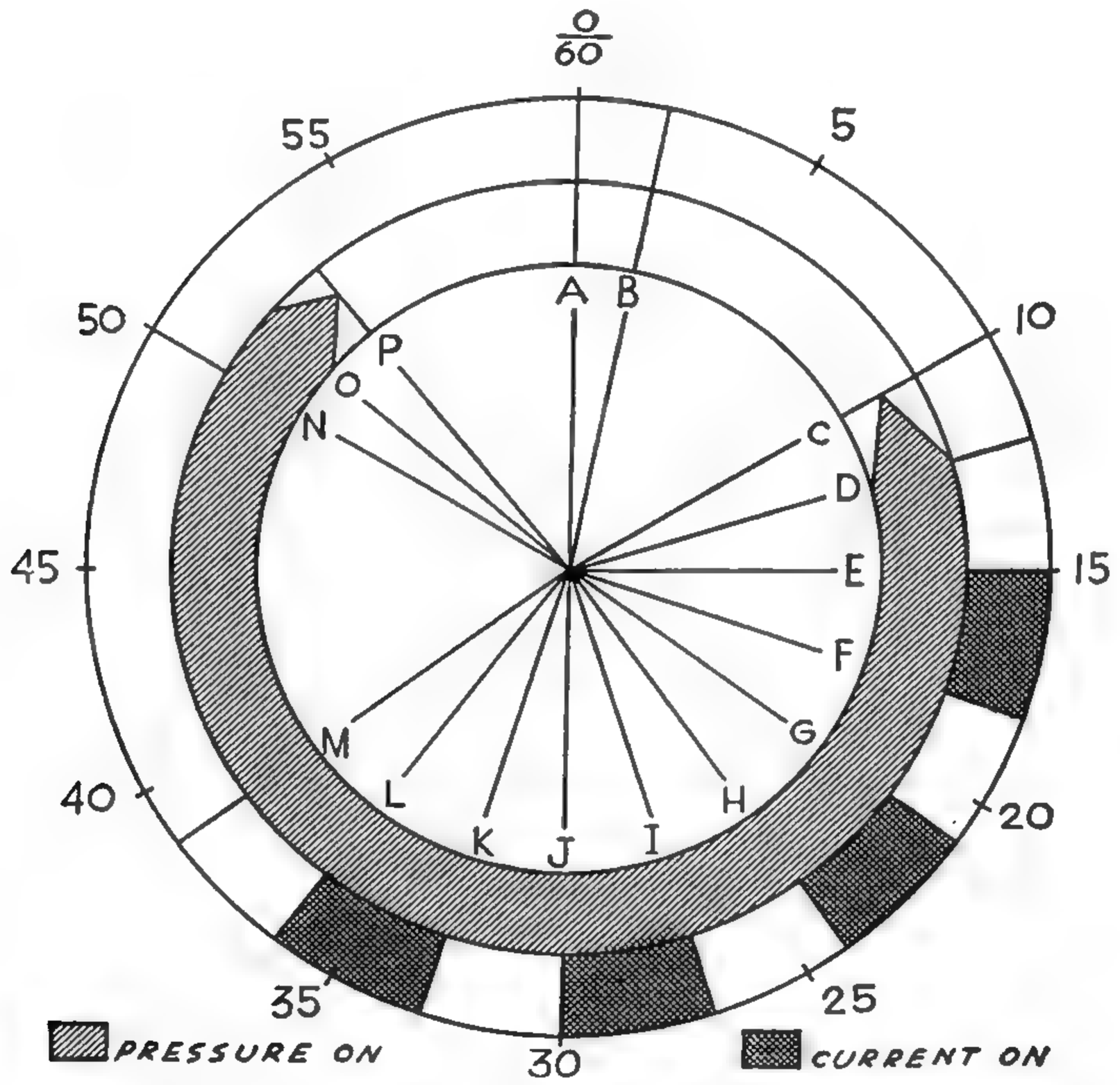


Fig. 22.—Complete Operating Cycle for Pulsation Spot Weld

Welding timers and sequence controls have now been reduced to a few types which fill most commercial applications:

NEMA Type 1A—This is a simple timer which controls a single function. It is used on cam-operated machines, or other places where a maintained pilot contact is provided.

NEMA Type 1B—This is a timer which controls an On and Off Time, and is used for pulsation welding where the total elapsed time or time interval for use with a synchronous panel and provides the same functions as 5B.

For the welding of various types of alloy steels, with their attendant metallurgical problems, controls have been designed to provide preheat and postheat, as well as more complex program controls.

Figure 22 shows a complete operating cycle when using either a *5B* or *9B* timer or sequence panel and specifically when operating at a speed of 60 strokes

per minute. Each complete stroke requires one second and this operation cycle is marked off in cycles or 60ths of a second.

Starting at *A*, the operator presses the foot switch which energizes the operating coil of the solenoid valve and at the same time energizes the squeeze period of the timer.

At *B* the solenoid valve has operated and passed sufficient air to start the head on its downward stroke.

At *C* the upper electrode contacts the work, stopping further motion, at which point pressure begins building up on the work.

At *D* full pressure is established, but an additional period to *E* is allowed for safety.

E marks the end of the squeeze time and start of weld interval and welding current starts.

At *F* welding current stops, starts again at *G*, off at *H*, on at *I*, off at *J*, on at *K* and finally off at *L*.

M marks the end of the weld interval and start of hold time.

At *N*, the hold time ends and the solenoid valve is de-energized.

At *O* reversal of air in the cylinder starts, and at *P* sufficient reversal has taken place to reduce the pressure to zero and start the head up, and at *A* the head has come to rest in its up position completing the cycle.

The diagram is proportioned to give the following settings:

Squeeze time: 15 cycles (0–15).
Weld interval: 24 cycles (15–39) (4 pulsations each 3 cycles on and 3 cycles off).
Hold time: 11 cycles (39–50).
Off time: 10 cycles (50–60).

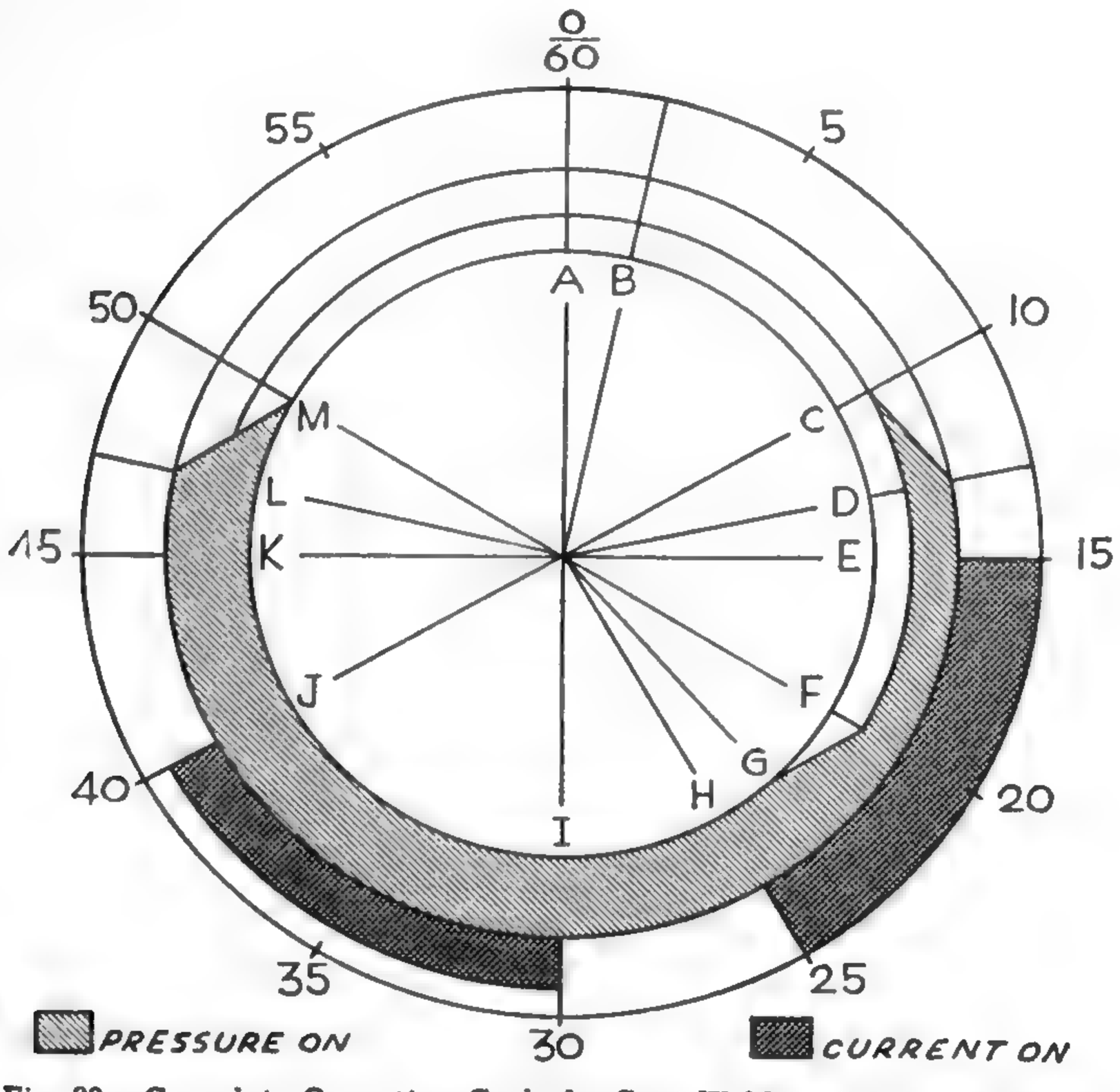


Fig. 23.—Complete Operating Cycle for Spot Weld with Forging Pressure and Postheat

In this setup, the time allowed for positioning the work is from *P* to *C* (16 cycles, or slightly over 1/4 second).

The chart does not take into consideration the time required for the timer relays to operate, as this requires 1/8 cycle or less and can be disregarded or included in the time allowances for the various functions.

Figure 23 shows a typical operating

cycle for a single impulse weld but provided with forge pressure and postheat. This is also based on an overall operation time of one second.

At *A* the foot switch is depressed, and at *B* the head starts down and contacts the work at *C*, establishing full pressure at *D*.

At *E* welding current is initiated. At *F* forge pressure is initiated, reaching its full value at *G* or about two cycles before the end of the weld time *H*.

At *I* postheat current is initiated, ending at *J*. At *K* the solenoid valve is deenergized, and at *L* welding pressure falls off, reaching zero at *M*. The return stroke is completed at *A* and the operation is then repeated.

The diagram is proportioned to give the following settings:

Squeeze time: 15 cycles (0–15).
Weld time: 10 cycles (15–25).
Postheat time: 10 cycles (30–40).
Forge time: 24 cycles (23–47).
Off time: 10 cycles (50–60).

It will be noted that the welding pressure is less than the forging pressure, but the welding current is greater than the postheat current. Also full forging pressure is attained just before the end of the weld time.

Special controls can be obtained which will provide many variations in the timing periods.

Timing periods of standard timers are shown in Table 1. Most timers are calibrated directly in cycles.

by means of taps on the welding transformer or by series-parallel connections or by taps on an auto-transformer or by any combination of these variable connections.

The electronic method of heat control consists of a device to delay the firing of the ignitron tubes each half-cycle the current flows and is commonly called *Phase Shift Heat Control.* As this firing point on the current half wave is retarded, the actual power delivered is reduced, which produces essentially the same effect as a reduction of voltage on the welding transformer.

Complete control from 100% to zero is not feasible, and it is necessary to limit the minimum value to 40% rms. current for 220-volt applications, and 20% rms. current for applications of 440 volt or higher.

Preheat and Postheat Controls

A preheat control is an additional element interposed between squeeze time and weld time or weld interval to provide a preheating period. In addition to being a time control, it is also usually provided with an auxiliary heat control station so that this preheat current value can be controlled independently of the welding current.

A postheat control is the same as a preheat control except that it is interposed between the weld time and hold time. This control is often used on air-hardenable steels to prevent too rapid cooling of the weld.

Table 1—Range of Standard Weld Timers, Pulsation Weld Timers, Sequence Weld Timers and Sequence Timers

Function	Timer Types	Adjustment (Range in Cycles) 60	50	25
Weld	1A	3-120	3-100	2-50
Squeeze	3B—5B—7B—9B	3-120	3-100	2-50
Weld	3B—5B	3-30	3-25	2-13
Weld interval	1B 5B 9B	9-360	8-300	4-150
Heat	1B 5B	3-30	3-25	2-13
Cool	1B 5B 9B	3-30	3-25	2-13
Hold	3B—5B—7B—9B	3-60	3-50	2-25
Off	3B—5B—7B—9B	3-60	3-50	2-25

Heat Control

The control of heat or current output of the welding machine to the work is accomplished in two ways: by varying the output voltage of the welding transformer and by electronic means. The output voltage may be adjustable either

Voltage Regulator

The function of a voltage regulator is to maintain consistency of welds with varying line voltage conditions. This is available for use with synchronous or nonsynchronous electronic timing controls which include heat control by the phase

shift method. This regulating compensator consists of an electronic circuit which maintains the rms. value of the welding transformer primary current constant within plus or minus 2% for line voltage changes of plus 10% and minus 20% provided other controls will function properly over this range. Under these conditions, the maximum normal setting of the welding machine current by heat control should not exceed 80% full machine output. The unit will compensate in less than three cycles for a sudden drop in voltage. This unit is adapted for welding systems where the power factor is in the range from 20 to 70%.

Current Regulator

The function of this unit is to provide consistency of welds with a given time and current setting on the controls where fluctuations in the welding current occur due to variation in line voltage or to change in the electrical constants of the welding circuit (such as inserting magnetic material in the throat of a welding machine and changing the overall reactance). This current-regulating control will maintain the welding current plus or minus 2% of its normal preset value, for any combination of changes in the load circuit which would normally have caused the unregulated current to change by plus or minus 20%. If welding current is flowing continuously, the regulator will correct fully, within three cycles, a change of voltage or impedance. However, the device will not operate satisfactorily with a current on time of 5 cycles or less, nor with a cool time of less than 4 cycles.

Within the limits of heat control adjustment, sudden variations of plus 10% to minus 25% in line voltage can be compensated; however, the allowable voltage deviation may be limited by other electronic control used with the regulator. To meet these specifications the heat control setting of the apparatus must not exceed 75% full machine current output.

ELECTRICAL CHARACTERISTICS

The electrical system of a single-phase a.c. resistance welding machine consists of (*a*) transformers and regulator, (*b*) secondary circuit, including electrodes and (*c*) controls.

The welding transformer in principle is the same as any other iron core transformer. The principal difference is that due to the low secondary voltage (2 to 20 volts) and very high secondary current (5000 to 100,000 amp.), the secondary usually is a copper casting with only one turn or, in the case of portable types, two or three for the higher voltages. The primary is wound with strip copper and the secondary is water cooled. The regulator is a tap changer for switching turns of the primary winding in or out to obtain a range of secondary voltages.

Transformer Ratings

The electrical rating of welding machines is based on their transformer rating or capacity. This rating is a thermal rating and has nothing to do with welding capacity. The nameplate rating in kva. is based upon ability to carry the rated current on a 50% duty cycle basis (see RWMA published standards). Thus, a 100 kva. welding transformer can carry a 100-kva. load for 30 min. out of each hour. Power distribution transformers are rated on a 100% duty cycle basis. Therefore a power distribution transformer rated at 70.7 kva. would have a rating comparable to a 100-kva. welding transformer.

Welding transformers, however, operate at much lower duty cycles. Therefore their actual output is usually many times their thermal rating.

Since the kva. rating of a transformer specifies the kva. load which it can carry at its rated duty cycle without exceeding a specified temperature rise, the rating is thus determined by the rate at which the internally generated heat can be dissipated through its cooling system. The rate at which heat is generated within the transformer increases very rapidly as the load exceeds the transformer rating and, in order to limit the amount of heat generated, it is necessary to limit the time that the transformer is actually carrying current by decreasing the operating duty cycle of the transformer. For example, consider a 100-kva. transformer rated at 50% duty cycle. This transformer could supply 100 kva. to a machine for 10 sec. in every 20 sec. (50% duty cycle) for an indefinite period of time. The same 100-kva. transformer, however, could supply 200 kva. to a machine without overheating if the on time is reduced to $2^1/_2$ sec. in every 20 sec. ($12^1/_2$% duty cycle).

The duty cycle of a transformer is defined as the percentage of time the transformer is actually carrying current and may be expressed by the following formula:

$$\% \text{ duty cycle} = \frac{\text{Current On time}}{\text{Current On time} + \text{Current Off time}} \times 100$$

Secondary Circuit

The secondary circuit or *welding loop* is usually considered as that portion of the welding machine having the fundamental function of conducting the high secondary current between the secondary terminals of the welding transformer and the electrodes. This secondary circuit is usually composed of the following elements:

1. Lower transformer connection between the transformer and the lower electrode holder.
2. Lower electrode holder.
3. Lower electrode.
4. Upper transformer connection between the transformer and the upper electrode holder.
5. Upper electrode holder.
6. Upper electrode.
7. Flexible conductor element to permit a relative movement between the upper and lower electrode holders.

The secondary current output of the machine in amperes is equal to the secondary voltage of the transformer divided by the impedance of the secondary circuit. The impedance is determined by the size of the secondary conductors, their arrangement or geometry and the frequency of the supply current. The throat depth and throat height or gap constitute the geometry.

It is well to remember a few general principles regarding the secondary circuit:

1. With a given secondary voltage the welding current will decrease as the throat depth or throat gap is increased.
2. The power factor will decrease with increasing throat depth, and will decrease more rapidly with increasing throat gap.
3. With the welding of increasingly heavier materials which do not extend into the throat, the reactance is unchanged, but the resistance increases, and the power factor increases.
4. Since reactive current is proportional to the frequency, the impedance of the secondary is considerably less on 25 cycles than on 60 cycles. Consequently, for a given secondary current, less secondary voltage is required. Since the primary demand in kva. is proportional to the square of the secondary voltage, considerably less kva. is required. This reduction in kva. demand will amount to 25 to 50%, depending upon the geometry of the machine and the work; 40% is a general average.

POWER FACTOR CORRECTION

Series Capacitors

One of the most serious handicaps to the use of resistance welding is its characteristic short time heavy load at low power factor.

One common method of improving the power factor is through the use of series capacitors. A capacitor is a low leading power factor device, while the welding machine is a low lagging power factor device. Therefore, if the two are connected in series with the proper ratio of capacitance to inductance, the resultant demand from the line can be made to approximate 100% power factor. To accomplish this, however, a welding machine must have either an especially wound welding transformer or an autotransformer and it is necessary to *tune* the machine with the job it performs to the proper amount of capacitance. Or, the machine may be tuned to unity power factor at its maximum demand, then on lesser demands the power factor will be less than unity. However, as the load is decreased, the kva. demand cannot increase above that for maximum load, in spite of the reduced power factor.

In general, it is not practical to use transformer taps where series capacitors are used because of the difficulty of obtaining proper tuning. If the system is properly tuned for the high tap, it will be undertuned to lower taps, which may result in a lagging power factor.

The net result of a series capacitor system is the reduction of the welding current in amperes being drawn from the supply lines for any given welding operation. The welding machine itself, will continue to operate at its natural power factor regardless of whether capacitors are used or not. Without the use of capaci-

tors, the current will be increased as determined by its power factor. With the use of capacitors, the voltage across the welding transformer will be increased, also as determined by the machine power factor. Thus, if a 440-volt machine operating at 50% power factor draws 300 amp. without the use of capacitors (132 kva.), it will draw 150 amp. when corrected to unity power factor, but the voltage across the transformer will be 880—still 132 kva. However, this increased voltage is supplied by the capacitors and not taken from the supply lines.

Also, the capacitors themselves will operate at higher than line voltage, depending on the amount of correction required. This voltage may be as high as three times line voltage, therefore, both the transformer and control panel must be built for high voltage service, as well as the interconnecting cables.

A discharge resistor and contactor is provided on all series capacitor installations to automatically discharge and short circuit the capacitors when the line switch is opened.

Shunt Capacitors

Shunt capacitors can be applied to some types of welding machines, although their use is very much restricted due to short timing periods involved. Since the initial inrush of current is high, this inrush may actually increase the demand from the line, thus defeating their purpose. If the welding time is comparatively long, such as in non-interrupted seam welding, shunt capacitors may show an advantage over series capacitors.

The use of capacitors, either series or shunt type, is strictly a matter of power supply and has no effect on the weld, although in some cases, the machine is much more sensitive to work resistance or other variables when operated at high power factors.

Local conditions invariably determine the necessity for power factor correction. If adequate power is available and power factor is not too important, capacitors can hardly be justified. But, with a limited power supply, or a power factor penalty or bonus, the use of capacitors may be necessary or desirable.

THREE-PHASE MACHINES

As resistance-welding machines have developed into increasingly larger and larger units, especially spot and projection welding machines, they have become increasingly difficult to operate from existing power lines and facilities.

The earliest attempt to alleviate this condition was with the use of motor-generator sets. With this method, the power could be taken from a three-phase line, equally divided between the three phases. In addition to taking the load from the three phases, it also reduced the peak demand to a certain extent, depending on the flywheel effect provided.

However, this method has two very serious disadvantages. First, the cost is usually prohibitive, often amounting to several times that of the welding machines they service. Second, the voltage regulation is very poor.

Another method of taking power from three phases is by transformation, such as with a Scott connection. This, however, does not provide equal phase distribution, and the advantage it offers is open to debate

Within the past few years, three separate systems have been introduced for distributing resistance welding loads essentially equally over all three phases. Each of these, however, must at this writing, be considered to be in the developmental stage, in spite of the fact that numerous installations have been made. These three systems are commonly known as *frequency converter, dry-disc rectifier* and *homo-polar.*

Frequency Converter System

This machine is provided with a special welding transformer with three-phase primary and common, or single-phase, secondary. The current in the three windings is controlled by ignitron tubes. The result is such that first one phase or winding of the transformer is active, then another, then the third, and repeating. This delivers to the secondary winding a single-phase current of low frequency (usually 5 to 12 cycles).

This secondary current, however, is not sinusoidal such as supplied by the incoming lines, but is a wave consisting of the basic low-frequency wave accompanied by waves of the natural frequency of the line. But the low frequency prevails and the reactance of the secondary circuit is somewhat lower than that of an

equivalent single-phase machine. This reduced reactance increases the power factor, which in turn, reduces the demand from the power lines.

Figure 24 shows simplified connections for the frequency converter system. While the total load supplied to the machine is divided equally between the three phases, the total load at any instant is taken from a single phase. The *flicker* effect has not as yet been completely analyzed.

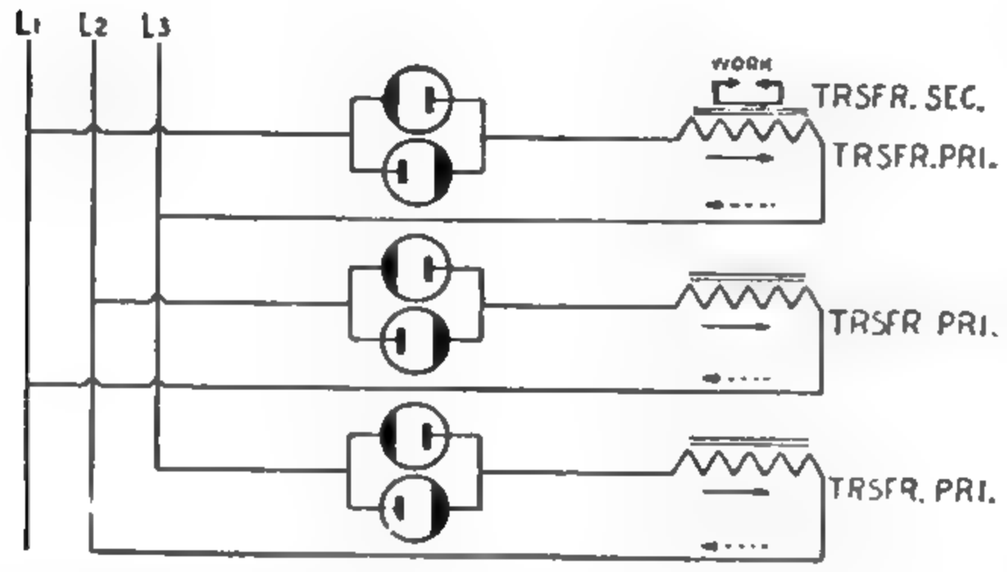


Fig. 24.—Electronic Frequency Converter System

Dry-Disc Rectifier System

A three-phase dry-disc rectifier machine that is capable of delivering direct current into the secondary of the welding machine, making it possible to produce a three-phase lower kva. demand than the conventional single-phase machine, is one means of handling the problems of lowering the high instantaneous demands found in the single-phase a.c. welding machine. This type of system can be used for a seam, spot or pulsation welding machine and may be applicable to flash-welding machines. The rectifier stacks have an exceptionally long life, are small in size as compared to other types of electrical components, and are of rugged construction. They are very suitable to welding type load, being capable of standing heavy current overloads. For the most economical transformer design and most satisfactory rectified wave form for the particular d.c. output voltage and current required in a resistance welding machine of this type, the rectifier circuit should be three-phase full wave (see Fig. 25). The dry-disc rectifier type of machine uses no welding transformer and with the three-phase full-wave circuit, in comparison with the three-phase half-wave circuit, it is much more efficient and economical.

Due to the resistance and inductance values the rate and rise of current in a dry-disc rectifier machine is slow, making it very desirable for projection and upset welding. The current rise is faster than any values calculated from R and L, due to the fact that the load sees a changing voltage. At the start of the current rise, the applied voltage makes the current start in a manner that makes the apparent maximum current about twice the actual maximum. Approximately 8 millisec. after start of current, the voltage drops to a low constant value because of the overshooting tendency of the current rise pattern. This rate of rise of current to maximum may be detrimental in some types of aluminum welding, but again in consideration of the values of kva. demands, more secondary current can be forced into the weld to overcome the effects of the slow rate of rise in current, and thus keep down the kva. demand

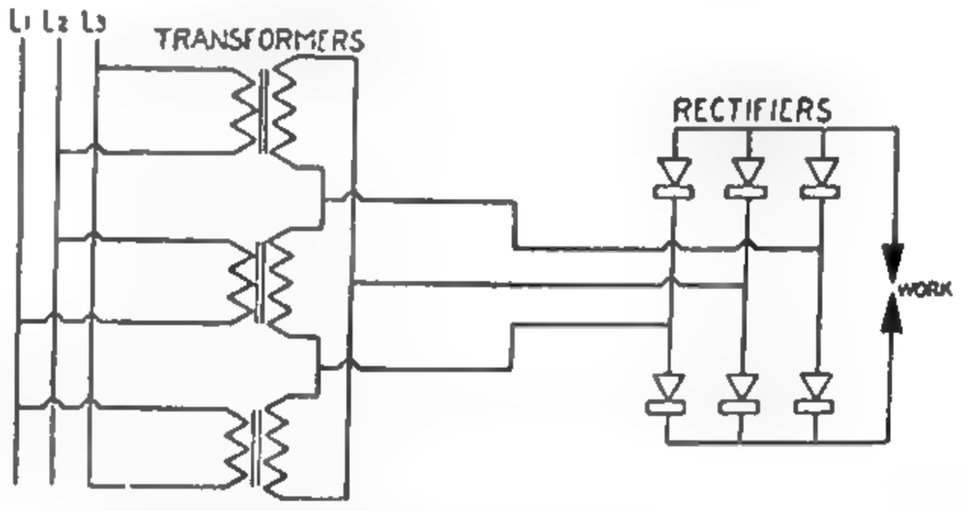


Fig. 25.—Three-Phase Full Wave Circuit of D.C. Dry-Disc Rectifier

when welding a given thickness of aluminum in comparison to single phase a.c. welding.

One factor requiring consideration in the application of dry-disc rectifiers in welding machines is a proper analysis of the efficiency. A study of the impedance curve and the efficiency measurements will show that efficiencies are lowest at low-current and low-impedance load. With a given load impedance, the efficiency improves as the current increases. With a given current, the efficiency will improve up to a point where the load impedance equals the rectifier impedance. With a resistance welding application there is no object in attempting to operate the rectifiers at maximum efficiency as long as the impedance adjustment must be in the load circuit and not in the rectifiers

themselves. However, there is no advantage in having a high efficiency, unless the high efficiency can be gained by lowering the rectifier impedance.

Homo-polar Generator System

Another method of obtaining a single-phase welding load from a three-phase line is by the use of a homo-polar generator. This apparatus consists of a conventional three-phase induction motor driving a uni-directional generator. On the same shaft is mounted a flywheel which stores kinetic energy, which gives the system a stored energy system in addition to providing the three-phase load.

Figure 26 shows the essential elements of the generator equipment.

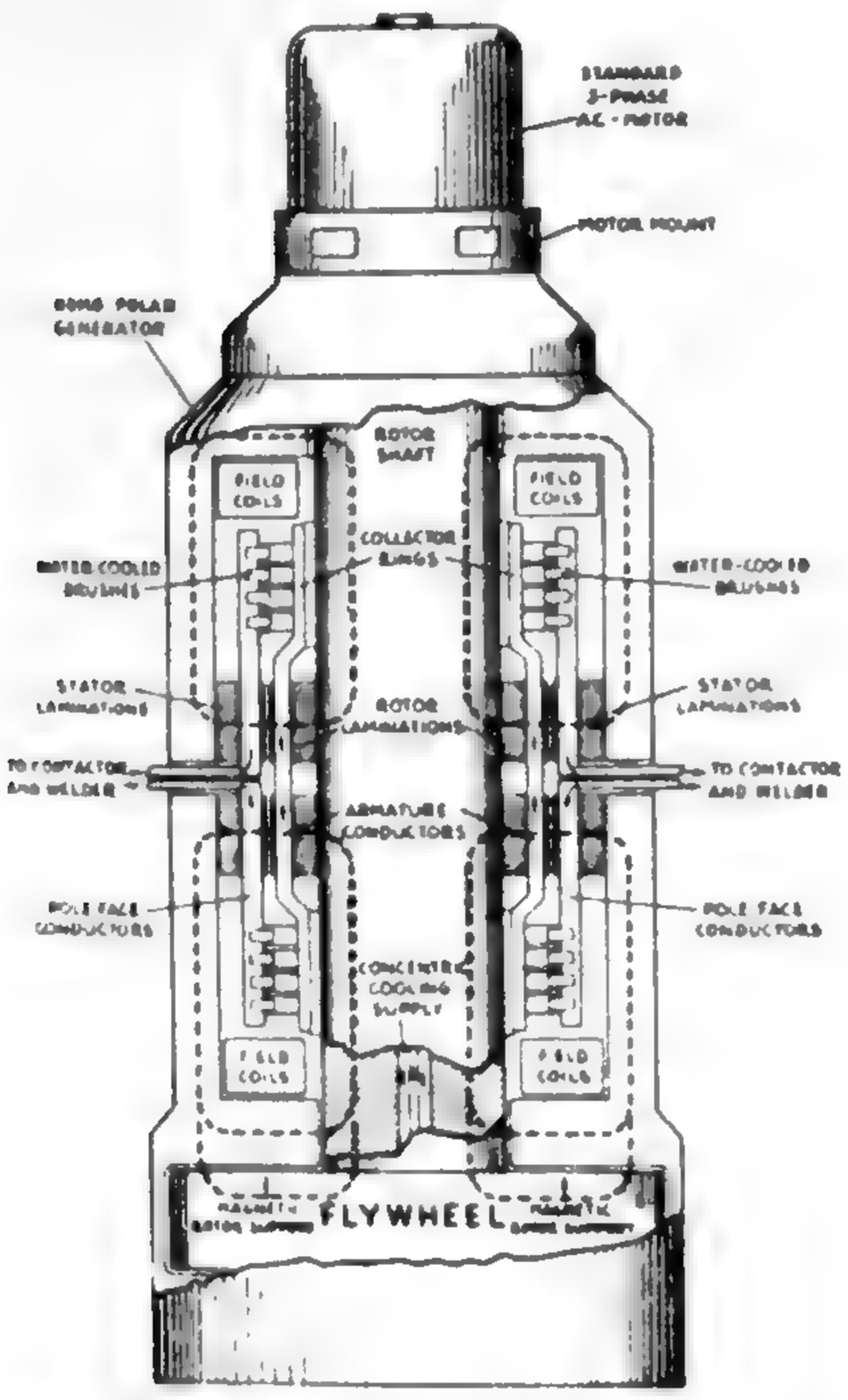


Fig. 26.—Schematic Cross-Sectional View of Motor-Generator Flywheel Unit

Due to the fact that the homo-polar generator has, effectively, only one armature conductor, the induced voltage for a given speed is determined by the number of lines of flux cut by this conductor each revolution. All of this flux must pass axially along the rotor core through the collector ring and the diameter of the latter must be held down to keep brush velocities within a reasonable range. These considerations led to the design of a machine that is actually two generators back-to-back with their rotors joined axially and their armature conductors joined directly in series so that their induced voltages are additive and each unit needs to develop but half of the required machine voltage.

Referring to Fig. 26, we can see that the generator unit is symmetrical about a horizontal plane through its approximate center. The dotted lines show the field flux linkage paths through each half of the unit and it should be understood that the direction of flux is opposite in the two ends of the rotor so that there is no tendency for interaction between the two magnetic circuits and so that the polarities of the induced voltages make them additive.

Compensation is effected by bringing the brush leads out through pole-face conductors through the stator laminations. It will be seen that load current flowing in these conductors is opposite in direction to that flowing in the armature conductors located close to the air gap on the other side of it. Hence the tendency of the current in the armature bars to rotate, distort or collapse the field flux is substantially canceled by the opposing action of the current in the stator pole-face bars. The use of open slots for the conductors aids this action without changing the induced voltage.

Further, a compounding effect is ob tained by skewing the rotor bars between the collector rings and the rotor laminations in such a direction that load current flows partially around the rotor and the consequent ampere turns aid the field excitation coils.

Voltage or heat control is obtained by adjusting the field excitation. By proper choice of motor size and characteristics, and fly-wheel size, a combination can be matched to almost any program of spot, projection or flash welding within the voltage-current capacity of the machine.

Since the output is direct current, throat area of the welding machine is of little consequence.

The contactor employed to control the output to welding electrodes is of the carbon-pile type and operated by an air cylinder. Conventional sequence-weld controls are used to time and sequence the machine and the contactor.

STORED-ENERGY MACHINES

Stored-energy welding machines are of three general types—electrostatic, electromagnetic and electrochemical. All three types accomplish the same basic purpose of taking power from a three-phase line, storing it, then suddenly discharging it to make the weld.

Motor-generator sets with large flywheels have been used in the past, but are now practically obsolete due to their high initial cost, maintenance and difficulty in maintaining proper voltage regulation.

The principle of stored energy has been applied extensively to spot welding and has had some applications for roller seam or roller spot welding. Electrostatic and electromagnetic types are not considered applicable for flash welding nor very heavy projection welding, due to their limited energy storage capacity. The electrochemical type, on the other hand, can be adapted to flash and heavy projection welding due to its very great energy storage capacity.

Electrostatic Stored-Energy Machines

In electrostatic stored-energy (capacitor discharge) machines, the energy charge is stored in capacitors or condensers. The mechanical analogy of this type of machine is a water storage tank or reservoir. The quantity of water and the rate at which it can be withdrawn are governed only by the size of the tank and size of discharge pipe. However, the supply line is much smaller. In this analogy, the capacity of the capacitor bank in microfarads corresponds to the size of the water tank, and the impedance of the welding machine corresponds to the size of the discharge pipe.

The principle of the electrostatic or capacitor method of stored-energy welding is illustrated in Fig. 27. It can be seen that it consists primarily of a power breaker for overload protection, a three-phase Delta-Y-line rectifier transformer, a three-phase full-wave grid control thyratron rectifier, a resistance voltage divider, an energy storage capacitor bank, shunt ignitron tube, discharge contactors or discharge ignitron tubes, a center tapped welding transformer, a vacuum tube leveling circuit and a voltage leveling potentiometer. The three-phase full-wave rectifier, *3*, for charging the main capacitor bank, *5*, utilizes a grid control thyratron tube for furnishing a d.c. supply and an inherent controllable device for predetermining and maintaining the capacitor voltage level. During the instant of recharging the capacitors, the value of rectifier current is determined by the impedance of the rectifier transformer, *2*, and the resistance of resistor, *12*. The values of impedance and resistance are such as to limit the current to the maximum current rating of the rectifier tubes. Starting with zero at the instant of start of charge, the voltage across resistance *4* increases with time

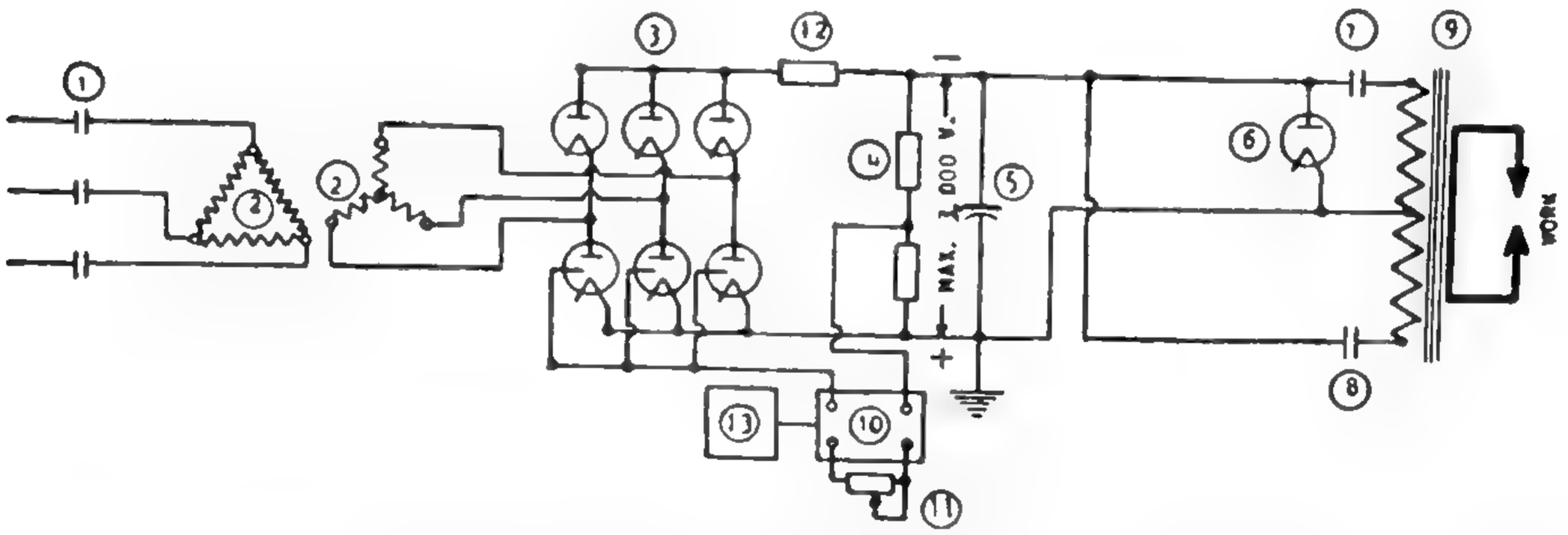


Fig. 27.—Schematic Diagram Showing Principle of Operation of Electrostatic Stored-Energy System for Spot Welding

1, Power breaker for overload protection; *2*, Three-phase Delta-Y rectifier transformer; *3*, Three-phase full wave, grid controlled, thyratron rectifier; *4*, Resistance voltage divider; *5*, Energy-storage capacitor bank; *6*, Shunt ignitron tube; *7*, *8*, Discharge contactors (alternate closure); *9*, Center-tapped welding transformer; *10*, Vacuum tube leveling circuit; *11*, Voltage leveling potentiometer; *12*, Resistor; *13*, Rectifier blocking circuit.

until it is great enough to oppose the preselected voltage at potentiometer *11*.

The leveling circuit, *10*, is generally made up of the ordinary radio-tube type circuit and the necessary d.c. positive bias and negative bias voltages for proper on conduction of the rectifier tube and cut off or off conduction time of the rectifier tube. The voltage, predetermined across capacitors, *5*, generally is predetermined from a range of 1000 to 3000 volts by potentiometer *11*. When the contactor, *7*, is closed, discharging the capacitor energy into the welding transformer, current flows in one-half of the center tapped welding transformer. At the instant of closure of contactor *7* the rectifier tubes are automatically cut off by reversing the bias on the grid of the thyratron tubes to a high negative value. After discharge welding current ceases to flow, the rectifier tubes are made conductive by the reversal of the negative bias to a positive value and the capacitors are automatically recharged.

The shunt tube, *6*, is placed across the main capacitor bank, *5*, to prevent reverse voltage appearing across the capacitors.

Contactors *7* and *8* alternate during successive welds to prevent saturation of the welding transformer.

Figure 28 shows the build-up of the capacitor voltage, the closure of contacts *7* and *8*, allowing the discharge of the capacitor energy to form the welding current and shows the action of the shunt tube conduction when the capacitor voltage attempts to reverse. Once the welding current ceases to flow, the capacitors are automatically recharged during the periods of hold time and off time.

Electromagnetic Stored-Energy Machines

The principle of operation of the electromagnetic method of stored-energy resistance welding is illustrated diagrammatically in Fig. 29. A three-phase a.c. power supply is rectified to d.c. by means of an ignitron tube rectifier, the output of which usually lies between 150 and 200 volts. When this direct current is connected to the primary of the special transformer or reactor in the welding machine, energy is stored until the circuit is interrupted by means of a suitable contactor. At this time the energy is released into the secondary circuit in the form of a high peak current which falls exponentially to zero.

The energy stored in an electromagnetic system is kinetic, as it is not possible to maintain the accumulated energy in a static condition. The welding reactor consists of a specially designed transformer having both primary and secondary windings and an air gap in the iron core. As long as a d.c. voltage is applied

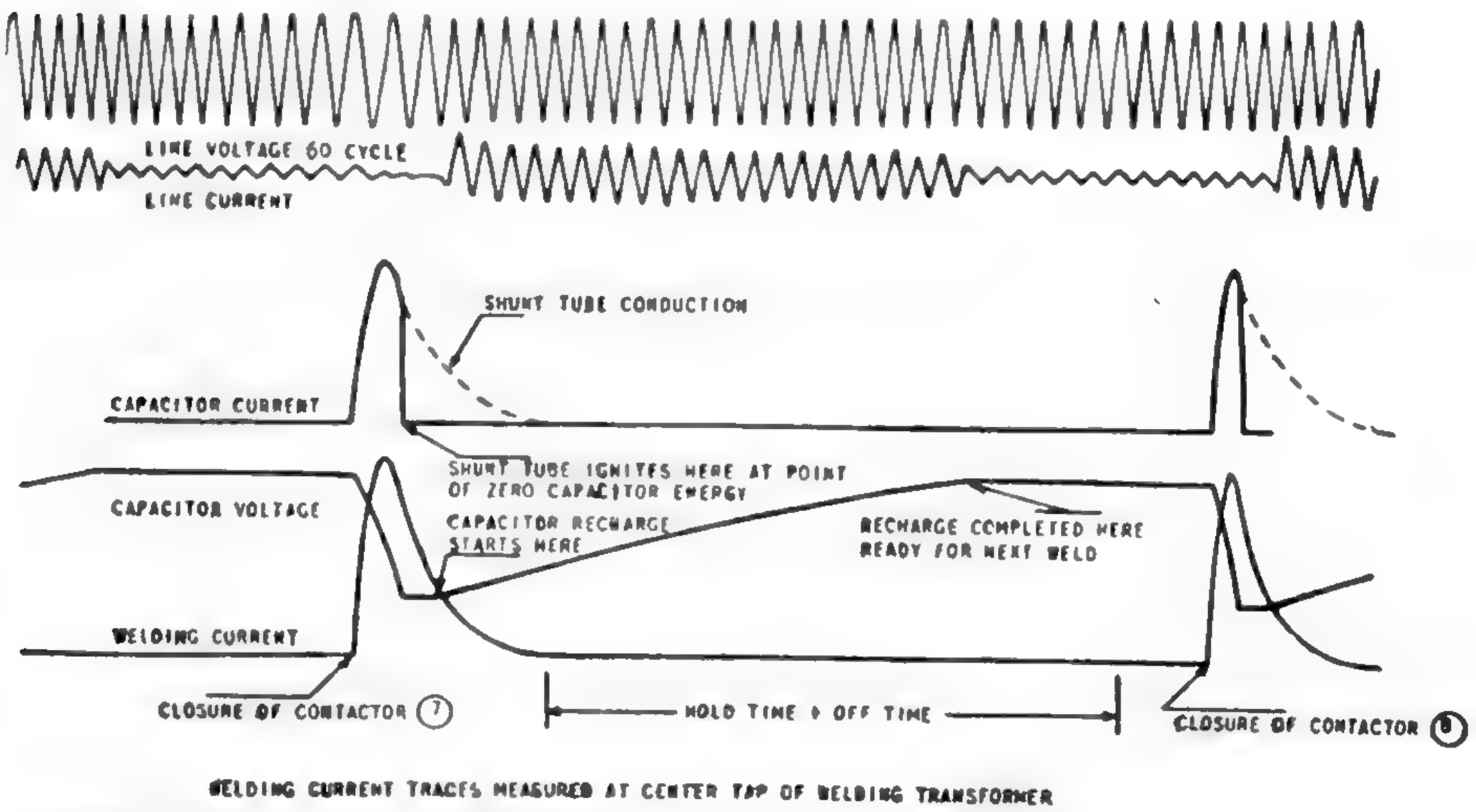


Fig. 28.—Oscillogram Showing Build-up and Discharge of Energy from Capacitors of Stored-Energy System Shown in Fig. 27

to the primary terminals of this reactor, the current increases nearly exponentially to some maximum value. While the primary current is increasing, it induces a voltage in the secondary winding which is proportional to the turn ratio and the rate of change in the primary current. This in turn produces a secondary current which rises to the maximum value very quickly then falls slowly to zero during the charge.

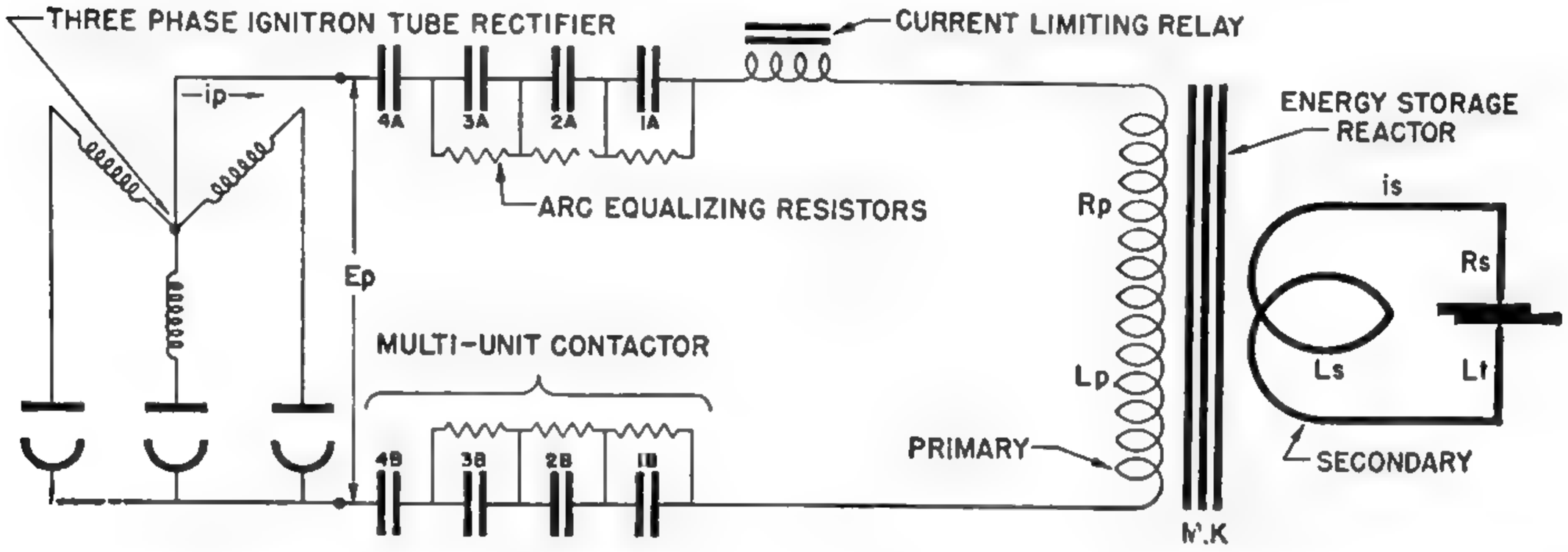


Fig. 29.—Schematic Diagram Showing Principle of Operation of Electromagnetic Stored-Energy System

Actually, unlike the above illustration, the primary current is always interrupted before its steady state value is reached. This is accomplished by means of a contactor of special design between the d.c. supply and the reactor. At a preset value of current, the primary circuit is opened rapidly, which causes the energy stored in the reactor to be transferred to the secondary or welding circuit. During the short period of primary current interruption, the secondary current rises from the negative peak to a very high positive peak, then falls to zero exponentially. In order to carry out the above process successfully, it is essential to use a current-interrupting device which will give reliable and consistent performance and which can withstand the high electrical and mechanical stresses which are developed during the opening operation.

Electrochemical Stored-Energy Machines

In electrochemical, or storage battery, resistance-welding machines, the electrical energy is stored in a storage battery. The equipment consists of a three-phase transformer, rectifier, contactor and storage battery, which may be applied to a conventional spot welding machine with the welding transformer removed.

Figure 30 shows the elementary circuit of the battery-operated welding machine.

The power input may be of any normal phase arrangement or shop voltage or frequency. The power is carried through a disconnect switch to a charge rate contactor. This contactor is a conventional motor reversing contactor controlled by a special sensitive contact-making voltmeter, *VM*. The contacts on the switch are connected to tap switches on the charger panel, permitting variation in charger transformer output voltage to the rectifiers, which, in turn, varies the charging rate to the battery. The purpose of the reversing switch and double sets of taps is to provide a dual charging rate.

For quick charge, or when operating on high-duty cycle, the high rate is applied; for maintaining the charge, and on low-duty cycle, the low rate is applied. When starting the machine, the voltmeter energizes the high rate contactor. As soon as the battery reaches approximately full charge, the voltmeter switches the charge to the low rate, and when full charge is reached, the low rate is cut off. On falling charge, the reverse sequence takes place. The purpose of the dual rate is to prevent the frequent switching which would occur if only a single rate were utilized. The voltmeter is connected across a pilot cell and the voltage of that cell determines the charging rate. Thus the voltage level or amount of charge in the battery or power pack is unaffected by variations in voltage of the power supply.

The rectifier is of the dry-disc type, copper-oxide, selenium, etc., and its output goes directly to the battery. As may be seen from the diagram, the output of the rectifier is added to the output of the battery for any given weld or discharge.

The battery itself is essentially a lead-acid battery, of a type especially designed for this service. The number, capacity and arrangement of the cells are selected to suit the range of work to be performed. The diagram shows a six-cell pattern connected series-parallel (2 cells in series, 3 pairs in parallel) to provide approximately 4 volts. The same battery could be connected 3 series, 2 parallel to deliver 6 volts. Other power packs provide 8, 12, 16, 24, 32 cells with various series-parallel arrangements to deliver the required current.

The secondary current output is regulated by a cast-iron adjustable resistor connected in series with the battery and welding electrodes.

cylinder is connected to the movable discs through a roller cam mechanism which multiplies the pressure of the air cylinder.

As in any carbon pile the resistance is inversely proportional to the pressure, therefore, the rate of rise of the current depends on how fast pressure can be exerted by the cylinder. By the use of large valves and connecting piping and fittings, this can be made very rapid. By means of speed control valves, the action can be slowed up if desired.

In opening, as pressure is removed, the resistance becomes quite high, so that just before the discs part, the resistance has become so great that the current is reduced nearly to zero, with the result that arcing is entirely eliminated.

The control of a battery-operated machine is the same as for the equivalent a.c. machine. Instead of a timer actuating the solenoid coil of a contactor, it actuates a solenoid valve for the pneumatic contactor. The sequence of operation is: the operator depresses the foot switch

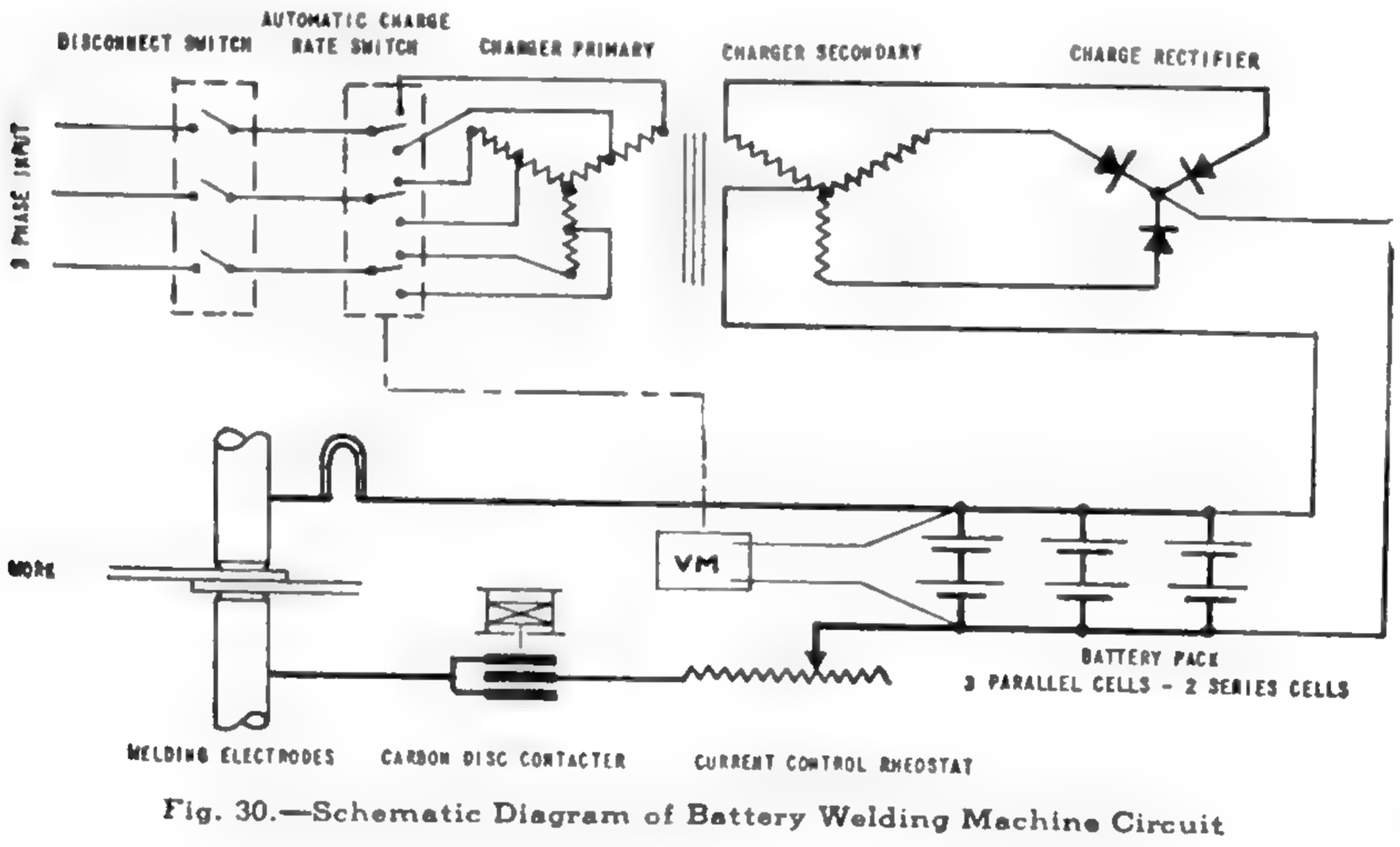


Fig. 30.—Schematic Diagram of Battery Welding Machine Circuit

The welding contactor operates on the principle of a carbon pile and consists essentially of two carbon discs normally held apart by springs. The movable disc is connected to an air cylinder which forces them together against the spring action. Actually, there are usually 3 discs—2 movable and 1 stationary. The purpose of the third disc is to double the capacity of the contactor with only slight increase in cost or space. The air

which initiates the timer and at the same time the solenoid valve for the main operating cylinder is energized. At the end of the squeeze period, the contactor solenoid is energized, then de-energized at the end of the weld period, and at the end of the hold period the main air cylinder is exhausted and the points separate.

The battery-operated system is adaptable to any form of resistance welding.

Its greatest advantage is in spot or projection welding. In seam welding with high duty cycle, it has little advantage. At the present time it is being developed for flash welding. Spot welding machines have operated continuously on a 20% duty cycle.

Percussion-Welding Machines

Percussion-welding machines, while truly stored-energy type machines, are not considered in the same category as other types of resistance welding machines because the principle of operation is entirely different. The machine is essentially an upset-welding machine and only work of this type can be performed on it. Power is taken from a three-phase line, transformed and rectified to about 3000-volts d.c., which is used to charge a bank of capacitors. So far, the operation is the same as an electrostatic stored-energy welding machine previously described, but here the similarity ends.

After the capacitors are charged, their terminals are directly connected to two sets of electrodes which clamp the work to be welded. The work-pieces are separated and insulated from one another sufficiently to withstand the high voltage to which they are now subjected. By means of a spring, one of the work-pieces travels toward the other at a high rate of speed, and when they approach to the arcing distance, as determined by the voltage to which the capacitors are charged, the capacitors discharge themselves through this gap creating an intense heat on the surfaces being welded. When the two pieces actually contact one another, the discharge is completed, and the two pieces forge together. (See Chapter 17 for further information on this process.)

POWER SUPPLY

Power Requirements

Power demand from the line is a function of the type of current and equipment employed. An adequate power supply is one of the prerequisites of present-day, high-production resistance welding. A major part of the power supply system for any industrial plant lies within the plant itself and consists of the power supply transformers and the power supply conductors.

Basically, the problem presented to power companies by resistance welding installations is that of carrying the fluctuating load without creating objectionable lamp flicker. The sudden and repeated flow of current to the machine through the impedance of the supply system causes an intermittent voltage drop, which, if great enough in magnitude, may cause flicker objectionable to lighting customers fed from that portion of the system. Resistance welding machines can cause two types of lamp flicker: a non-cyclical flicker from single-impulse machines such as spot or projection welding machines; and a cyclical flicker from seam welding machines or spot and projection welding machines equipped with pulsation control.

A non-cyclical or individual flicker is usually objectionable to most lighting customers if it causes the lamp voltage to drop more than two volts.

Sometimes this limit of two volts can be extended upward to three or four volts and, conversely, it may have to be revised downward to one and one-half volts, depending to a large extent upon the number of lighting customers affected. In some cases where a particularly large machine may affect a large area, such as might be fed from a 24-kv. bus, it may be prudent to set the design limit as low as one or one and one-half volts.

Cyclical flicker becomes evident, and may prove objectionable, whenever the frequency of occurrence exceeds one flicker a second. The borderline of objection follows a typical V-curve, dropping to a minimum of about $^1/_2$ volt at the worst frequency of 7 or 8 flickers per second.

Figure 31 shows objectionable limits of lamp flicker caused by resistance welding loads in voltage drop at the lamp. This refers to the momentary drop caused by the welding load only, without reference to overall plant voltage drop. A 115-volt lamp may operate at 115 volts at night, and 110 volts during day-load conditions. This 5-volt drop is not considered, but the welding load drop would refer to either the 110- or 115-volt normal voltage. The curve is the result of many studies on the subject, and may be considered as correct for 60-watt incandescent lamps. Larger lamps, due to their larger filaments, are less susceptible to voltage fluctuation, while fluorescent lamps are more

susceptible. This fact must be taken into consideration, due to the increasing use of fluorescent lamps.

Many seam welding machines operate at frequencies from one to four cycles on and from one to four cycles off, which is right in the cyclical range. Similarly, spot or projection welding machines, equipped with pulsation control to give a series of current pulses (so many cycles on and so many cycles off), may produce lamp flicker in the cyclical range.

Even if the frequency of a specific pulsation weld is fairly high up on either side of the V-curve, it is quite likely that some time during the life of the installation, the control will be changed, and the welds will be made at the worst frequency of some 7 or 8 pulses per second. Such a change in the frequency of pulsations can be easily made by a simple turn of the control dial, and so bring the operation anywhere within the entire range of cyclical flicker. For this reason, where either seam or spot- and projection-welding machines with pulsation control are concerned, it is usually necessary to design the machine service so that it will stay within the $^1/_2$-volt limit. Again, this $^1/_2$-volt, cyclical-flicker limit must of necessity be somewhat flexible, the same as the 2-volt, non-cyclical limit, and must be revised slightly upward or downward as conditions dictate.

Since no two power systems are alike, it is impossible to give any general rule as to how resistance welding machines of different sizes can be readily served.

Where the ohms impedance of the supply system is low, that is, near large sources of power, such as generating stations or large stepdown substations, large welding machines are easily served, without exceeding the predetermined flicker limit. It is obvious, however, that as the ohms impedance becomes greater, either through stepping down to a lower-voltage part of the system or through adding miles of line at any given voltage, the size of welding machine that can be handled, without exceeding the flicker limit, becomes smaller and smaller.

Where large plants are served at 24 kv. in established industrial areas, there is

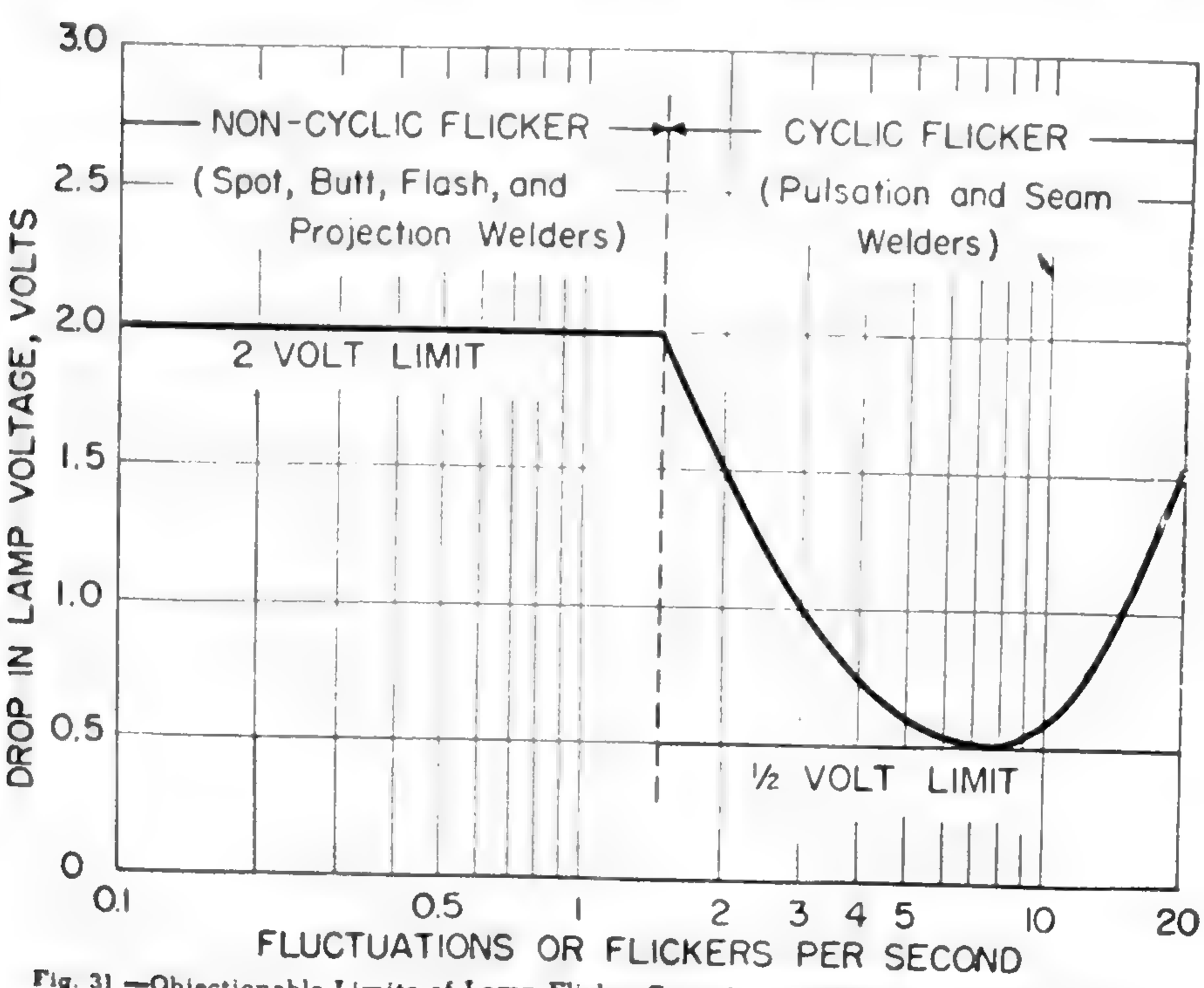


Fig. 31 —Objectionable Limits of Lamp Flicker Caused by Resistance-Welding Loads

practically no problem as far as large welding machines are concerned. They can be connected right in with the rest of the plant load. Other large plants that may be served at 4800 volts, even in the same general location, cannot ordinarily handle as large welding machines, because of the greater percentage of ohms impedance due to the lower voltage.

For the smaller plants in the industrial area that are served in common with other customers from 4800-volt lines, if one is not to disturb the other, the permissible welding demand must be reduced to values of the order of 200 to 500 kva. For similar plants in residential areas, away from the large stations, the size of machine that can be handled, even on the 4800-volt lines, is reduced to the order of 100 to 200 kva. Still farther out in a suburban area, the 4800-volt lines can accommodate welding demands in the range of only 50 to 100 kva.

In considering the installation of a resistance-welding machine, it is necessary to determine the kva. rating of the power-supply transformer required and the size of the power-supply conductors. The power supply transformer which is usually connected to a 2300- or 4000-volt primary feeder is installed external to the machine and should not be confused with the welding transformer mounted in the welding machine. The power supply conductors are the power leads between the power-supply transformer and the welding machine.

The selection of the power-supply transformer and supply conductors is governed by two factors—the permissible voltage drop and the permissible heating. The permissible voltage drop is the determining factor in the majority of installations but consideration must be given to both factors. In all cases, the final selection of the equipment must be determined by that factor which requires the larger transformer and the larger conductors.

It is relatively simple to determine the size of the power transformer on the basis of heating alone, inasmuch as the welder transformer is rated on a heating basis and a definite ratio exists between the two ratings. Power transformers are usually rated on a continuous or 100% duty cycle basis; whereas the welding transformer is rated on a 50% duty cycle basis, as previously explained. The power transformer rating required on a heating basis only for a given welding machine will, therefore, be equal to the welding transformer rating at 50% duty cycle divided by the square root of two. The square root of two is the conversion factor.

To find the size of the power transformer required on a heating basis for the proper operation of a 200-kva. seam-welding machine, this value can be substituted in the above formula as follows:

$$\frac{200 \text{ kva. } (50\% \text{ duty cycle})}{\sqrt{2}} = 141.4 \text{ kva.}$$

If there is more than a single machine to be served from a common power-supply transformer, a thorough study of actual operating duty cycles of all machines and the operating diversity factor between machines must be made. In actual practice, most welding machines except some seam welding machines usually operate below their maximum thermal capacity because the size of the transformer in the machine is dictated by the required welding current output rather than by thermal considerations. Tests of many installations shows that the values given in Table 2 are representative of actual field conditions. Thus, for instance, if the machines are predominately spot or projection welding machines, a power-supply transformer with a rating of 20% of the sum of the name plate ratings of the machines would, in most cases, be adequate as far as permissible heating is concerned.

Table 2—Equivalent Continuous Loading of Typical Welding Machine Installations

Type of Welding	Equivalent Continuous Load Expressed in Percent of Sum of Nameplate Ratings
Spot, projection (single impulse)	20
Spot, projection (pulsation)	40
Flash, multipoint spot or projection	20
Seam	70

In order to determine the size of the power supply transformer required to serve a welding machine on the basis of voltage drop, it will first be necessary to determine the maximum permissible voltage drop which can be tolerated. Where the same power transformer is used with two or more machines in such a manner that the voltage drop resulting from the operation of one machine will

be reflected in the operation of the second machine, it is advisable to confine the total maximum voltage drop to not more than 10% or, at the most 15%. All voltage drops should be measured at the locations of the machine and the percentage voltage drop should be calculated by means of the following formula:

$$\frac{\text{No load voltage} - \text{Full load voltage}}{\text{No load voltage}} \times 100 = \% \text{ voltage drop}$$

Likewise, where an electronic tube-type timer and contactor are employed, it will be necessary to hold to this limitation of 15% unless provisions are made to maintain the control voltage to the electronic tube panel. Where an electronic tube-type contactor is employed on a 220-volt circuit, it is advisable to limit the maximum voltage drop to 10%; however, in some cases for which a 10% limit would be difficult and the cost excessive, the upper limit of 15% may prove satisfactory.

The percentage of the total voltage drop that should be apportioned to the power transformer and the percentage that should be apportioned to the supply leads between the transformer and the welding machine involve a consideration of installation costs as well as the amount of voltage drop existing in the high voltage system ahead of the transformer. In most cases, very little can be done toward reducing the voltage drop in the high-voltage system at a cost commensurate with the expenditure needed for the same percentage reduction in the low-voltage system. Where more than one machine is involved, the largest machine of the group is always considered, with calculations of the diversity factor of other machines present in the group, when calculating voltage drop.

The high-voltage system regulation can be obtained from the local power company by giving them the maximum kva. and power factor that the largest welding machine will draw from the power system. The difference between the figure thus obtained and the total allowable 10 or 15% voltage drop is the allowable voltage drop in the step-down bank and secondary or low-voltage bus system.

A group of welding machines can be served either from a single-phase transformer bank or a three-phase bank, and where the welding load is large enough to justify a separate transformer bank for welding load only, it will be found advantageous and more economical to use a single-phase system. The load is single phase and it will remain single phase no matter how the transformers ahead of it are connected. Sometimes it is desirable to spread the individual single-phase loads over the three-phase wires for more economical utilization of the supply lines, but unless there are large numbers of machines connected, the necessity for balancing the load is not important. When there are many machines, they are usually scattered around in different parts of the plant so that several stepdown banks become necessary at different locations. In this case, individual single-phase banks can be connected to separate phases and thus bring about some semblance of balance on the supply wires.

A given kva. of single-phase load fed from a three-phase transformer bank will cause just twice as much transformer voltage drop as the same kva. load fed from the same capacity in transformers connected as a single-phase bank. It is thus obvious that, where the transformer voltage drop must be kept at a minimum, it is highly desirable and more economical to use single-phase, stepdown banks of transformers.

The voltage drop through the power transformer is a function of the characteristic called *transformer impedance*. This transformer impedance is a measure of the total restriction which the transformer offers to the flow of current and is usually expressed as a percentage of the rated voltage. The impedance value for standard power transformers is generally between 5 and 6% and is stamped upon the transformer nameplate. For the purpose of this discussion, this value can be interpreted as the percentage voltage drop through the transformer when rated kva. load is applied.

While the foregoing explanation is subject to correction for technical accuracy, the approximations indicated are sufficiently accurate in estimating the size of the power transformer required for supplying a given, *during weld* kva. demand with a given maximum voltage drop through the power transformer.

In general, the low-voltage bus or feeder from the transformer to the machines should always be as short as pos-

sible and of low reactance design in order to keep the voltage drop within the prescribed limits. Probably the simplest and cheapest bus construction consists of insulated wire, taped together and either hung on racks or pulled through conduit. One disadvantage of such construction is the lack of facilities for easily tapping off connections for welding machines throughout the bus length. When only two or three machines are to be served at a common location at considerable distance from the supply transformer this construction is cheap and effective.

A bus construction which permits easy tap connections at frequent intervals along its length is desired in production plants where manufacturing layouts are continually changing. With the welding bus extending the full length of the plant, machines can be moved about to meet the changing conditions without great trouble. The bus can be made up on the job or it can be purchased, prefabricated in unit lengths, either with or without enclosures. The copper spacing should be kept at a minimum. There are several standard designs of busses offered by different manufacturers particularly for welding loads.

By dividing the supply system into the three parts: (1) high-voltage system, (2) power transformer and (3) low-voltage feeder or bus, and providing a balanced layout so that the sum of the voltage drops in the three parts does not exceed the predetermined allowable standard, an adequate power supply is assured.

The entire subject of voltage drop and voltage regulation is too involved for complete coverage in this chapter. Wherever there is any question whatever concerning availability of power, it should be approached by competent engineering analysis.

Various attempts have been made to interlock two or more machines to prevent simultaneous firing. Any scheme of interlocking necessarily causes some curtailment in production. While this may not be serious on two or three machines, it can easily become a factor if more machines are interlocked. The interlocking of two or three machines may be the solution of a problem in some cases, but it is doubtful if the interlocking of more than three can ever be justified.

All of the foregoing discussion relates to voltage drop caused by the welding load as it affects the power supply system, with no consideration being given to the effect of this voltage drop on the welding machine itself, or the quality or consistency of its output.

If the voltage drop at the machine, or to put it more clearly, if the *during weld* voltage at the transformer terminals is constant, proper compensation can usually be provided through the machine controls. However, the *during weld* voltage at the machine may fluctuate as much as 10% at different times of the day, caused by voltage drop from other plant equipment.

For corrective measures to be taken for this condition, refer to voltage and current regulators in the section on controls in this chapter.

Electrical Protective Devices

Resistance-welding machines should be electrically connected to the power lines with the same care as other electrical apparatus. The cable installation should be made in accordance with electrical code standards, with adequate disconnecting switch and protective devices interposed between the machine and power lines.

As previously outlined, the cable size should be calculated both on a thermal and voltage drop basis.

It is generally desirable to use altogether separate circuits and protection for the control and welding power. This is, of course, a necessity when different voltages are used, as is common practice.

For the control circuit, it is usually satisfactory to use a simple enclosed fusible disconnect switch.

For the power or welding circuit enclosed fusible disconnects may be used and frequently are, but a more satisfactory protective device is an air-circuit breaker, such as supplied by a number of electrical manufacturers.

The rating of this breaker in carrying capacity should be sufficient to carry the maximum demand of the machine with its electrodes contacting without work in place. This may be from two to four times the machine nameplate rating. It is not considered possible to protect the machine against overload due to its variable demand and duty cycle, therefore, the protective device is intended for short-circuit protection only. One of the advantages of the circuit breaker over

fuses, is the fact that a push button can be located on the welding machine convenient to the operator to open it quickly in emergencies.

Circuit breakers are also rated in interrupting capacities. The required interrupting capacity for any given installation is a function of the impedance of the power supply from the breaker back to the power source. The power engineer should be consulted to insure adequate interrupting capacity.

When fuses are used, their size should be calculated not on a thermal basis, but on a modified demand basis. The circuit breaker operates on an instantaneous load, whereas fuses have a time lag, which gives some consideration to the duration of the load. Welding machine manufacturers provide wiring diagrams, in which fuse ratings are recommended. Generally, it is not necessary or desirable to fuse a machine to its maximum demand as required for a circuit breaker but on the other hand, the fuses should hold for any normal demand or operation of the machine. Again, about the only purpose of fuses is to interrupt a short circuit in the transformer, its controls or wiring.

MEASUREMENT

Primary Current

The simplest and probably one of the most reliable methods of measuring primary current is with an indicating ammeter. If the reading is taken during a regular weld, the time duration of the weld is too short in most cases for the pointer to come to a stop. Pointer-stop ammeters are available for such readings. A number of tests should be made, each time moving the stop up until the pointer barely moves from the stop. This, then, gives the actual demand with good accuracy. If a pointer-stop ammeter is not available, any ammeter may be used by removing the cover over the scale and using a pencil as a stop.

Another method that can be used is by ratio. If the secondary circuit is constant or unchanged, the primary current will be proportional to the voltage at the welding terminals. Table 3 shows relations of primary and secondary voltages and currents for a typical welding transformer.

Values given are for a typical transformer, 440 volts primary with 8 taps, with an assumed primary load of 100 amp. on the low tap. If the secondary circuit is not changed, primary and secondary currents for other taps will be as shown.

Table 3—Primary and Secondary Circuit Relationships

Tap No.	T.R.[a]	E_s	I_p	I_s	KVA
1	100	4.4	100	10,000	44
2	96	4.58	108.5	10,400	48
3	92	4.78	118	10,860	52
4	88	5.0	129	11,350	57
5	84	5.24	142	11,900	62
6	80	5.5	156	12,500	69
7	76	5.79	173	13,150	76
8	72	6.11	193	13,900	85

[a] T.R. = Turns ratio; E_s = Open-circuit secondary voltage; I_p = Primary current, amp.; I_s = Secondary current, amp.

Standard tests at machine manufacturer's factories provide for a prescribed secondary circuit (see RWMA *Resistance Welding Equipment Standards*), with a reduced voltage applied to the machine terminals. This reduced voltage remains on long enough to obtain a steady reading from a standard ammeter. A simultaneous voltage reading is also obtained, then the current in amperes at rated voltage will be proportional to the ratio of rated voltage to test voltage. Thus, if 55 volts applied causes a reading of 100 amp., the current at 440 volts will be $100 \times 8 = 800$ amp.

In the same way, the primary current for any tap may be calculated from the turn ratios of the various taps. (Turn ratios for various taps may be secured from the manufacturer, but in absence of this, they can be obtained by measuring the open-circuit secondary voltage for the various taps. For any tap, line voltage divided by open-circuit secondary voltage gives the turn ratio.)

Primary current can also be measured with an oscillograph, but for ordinary purposes, this involves too much time and equipment, and the results are no better.

Secondary Current

The simplest and most commonly accepted method of measuring secondary current is to merely multiply primary current by the turn ratio. While this method is subject to the errors and losses

of transformation, other methods introduce errors, the extent of which are hard to determine. Measuring the current by the voltage drop across a shunt placed in the secondary circuit has been done on a laboratory basis, but this is unsatisfactory due to the difficulty of placing the shunt in this circuit.

If primary voltage and current readings are obtained simultaneously, the kva. in demand is the product of the two. If a watt meter is added, and all three taken simultaneously, the kw. demand is also obtained, as well as the power factor of the machine. (Power factor is the kw. divided by the kva.)

Time

The best method of measuring welding time will depend on the type of weld being made, or to be more specific, the length of time to be measured or checked and the accuracy required. For long non-interrupted seam welds and for very long flash welds, an ordinary stop watch is sufficiently accurate. For spot-, projection- and high-speed flash welds a cycle counter is most suitable. This is an instrument driven by a synchronous motor and containing a large pointer, or hand, making one revolution per second and with a scale graduated in cycles. It is provided with a solenoid clutch automatically operated in such a manner that the welding time in cycles is metered off. This is usually sufficiently accurate for welding times of five cycles or more.

A cycle recorder draws a trace on a moving tape for each cycle passed. This is a little more accurate than the cycle counter, and is especially valuable for checking pulsation and interrupted seam-weld currents.

For more exact determinations of time, a magnetic oscillograph can be used. This instrument records the complete current wave, therefore, its recordings can be considered essentially correct. If the time to be measured does not exceed three or four cycles, a cathode-ray oscilloscope can be used, but it is useless for measuring time of greater duration.

Synchronous timers are designed to pass complete cycles and are calibrated in cycles, and this calibration can be assumed to be correct.

Non-synchronous timers are also graduated in cycles. The repetitive error in actual operation is about one cycle. This error can therefore be neglected if the time is 10 cycles or more. Under 10 cycles, the accuracy desired will determine whether or not this possible error can be tolerated.

Pressure

Pressure, or welding force, is a factor that is difficult to accurately measure or determine. The most commonly used method of determining pressure is by calculation. On air-operated machines, welding pressure is calculated from the piston area and air pressure per square inch. Packing friction and weight of the moving head are usually neglected. If packing friction is kept low, this method is usually sufficiently accurate. Pressure on hydraulic machines can be calculated in the same manner.

Pressures exerted by springs can be calculated from spring data readily obtainable.

Two or three types of pressure gages have been developed for measuring spot-weld electrode force directly.

None of the above methods takes into account the *reactive kick* of the secondary circuit. When a heavy current, such as a welding current, passes through parallel conductors, such as spot-welding horns, the conductors try to separate further. The extent of this kick can be readily demonstrated by duplex secondary cables of a portable machine. Unless bound or clamped, they will separate each time current is passed through them. The actual effect of this reactive kick depends on the magnitude of the current and the design of the secondary circuit. Usually, for all practical purposes, it can be neglected, but in some cases, it can exceed the mechanical pressure exerted and actually cause the electrodes to open during the weld.

Special spot-welding electrodes have been developed, incorporating an electronic strain gage and shunt which can be connected to two elements of an oscillograph for simultaneously recording net welding force, welding current and time. This device is sensitive to the reactive kick, and it can be separated on the oscillogram. (For further details on this instrument and other measuring and metering devices, refer to *RIVMA Manual*, Chapter 32.)

The upset pressure or force of flash

welding machines is not readily determined. For air and hydraulic machines it can be estimated by means outlined for press and spot welding machines. For hand-operated machines it can be roughly approximated by a calculation of the leverages and an estimate of the force exerted at the end of the lever.

It is impossible to even estimate the upset force of a motor-operated machine. While it would be possible to interpose a spring or fluid cylinder between the platen and cam follower, and measure the pressure in this manner, either the spring or cylinder would be quite bulky and the whole setup costly and cumbersome.

BIBLIOGRAPHY

1. *Resistance Welding Current Measurement*, E. W. Clark, The Welding Journal, March 1940.
2. *Power Supply for Resistance Welding Machines, Part 1—Guide to Good Electrical Performance of Resistance Welding Machines*, Transactions of the American Institute of Electrical Engineers, 1940. *Part 2—Resistance Welder Installations*, Transactions of the American Institute of Electrical Engineers, 1940. *Part 3—Factory Wiring for Resistance Welders*, Transactions of the American Institute of Electrical Engineers, 1941.
3. *Electrical Characteristics of Resistance Welders and the Proximity Effect of Work Materials*, J. H. Cooper, The Welding Journal, February 1942.
4. *Resistance Welding Fundamentals*, F. R. Woodward, The Welding Journal, February 1942.
5. *Electronic Control of Resistance Welding*, G. M. Chute, McGraw-Hill Book Co. 1945.
6. *Straight and Offset Resistance Welding Electrodes and Electrode Holders*, American Standard C52.3—1945, American Standards Association, Inc.
7. *Design and Construction of Resistance Welding Equipment*, American Standard C52.4—1945, American Standards Association, Inc.
8. *Electrical Power Systems for Resistance Welding Machines*, J. H. Cooper, The Welding Engineer, June 1945.
9. *Line Drop Produced by Resistance Welders*, R. L. Longini, Transactions of the American Institute of Electrical Engineers, September 1945.
10. *War Proved Advances in Low-Reactance Cable*, Myron Zuker, The Welding Journal, November 1945.
11. *Application of Capacitor Discharge to Welding*, H. J. Bichsel and J. R. Parsons, The Welding Journal, November 1945.
12. *RWMA Resistance Welding Manual*, Resistance Welder Manufacturers' Association, 1946.
13. *Influence of Magnetic Materials on the Welding Characteristics of Resistance Welding Machines*, J. J. Riley and C. E. Smith, Transactions of the American Institute of Electrical Engineers, 1946.
14. *Original Resistance Welder Design for Production of U.S. Navy 40 MM. Ammunition Boxes*, F. M. Pence, The Welding Journal, September 1946.
15. *Additional Timing Period of New Motor-Driven Control Increases Gun Welder Speed*, H. I. Stanback, The Welding Journal, November 1946.
16. *Resistance Welding with Storage Battery Power*, John D. Gordon, The Welding Journal, November 1946.
17. *Voltage Changes Due to Resistance Welder Loads*, Johnson, Peterson and Rhodes, Transactions of the American Institute of Electrical Engineers, 1947.
18. *Electric Resistance Welding Bibliography*, H. S. Card, 1947.
19. *Choice of Cable and Transformer Size for Portable Spot Welders*, Myron Zuker, The Welding Journal, March 1947.
20. *Three-Phase Balanced Load Resistance Welding Machines*, J. L. Solomon, The Welding Journal, May 1947.
21. *Spot Welders with Series Capacitators*, F. L. Brandt, The Welding Journal, June 1947.
22. *Series Capacitors for Increasing Voltage Regulation on Circuits Supplying Power to Resistance Welder Loads*, Bloomquist and Wilson, General Electric Review, June 1947.
23. *Batting Out Bug Bombs*, Athel F. Denham, The Welding Engineer, August 1947.
24. *Short Circuit Impedance in Spot Welding 1/8-, 1/4- and 1/2-In. Mild Steel*, Robert H. Blair, The Welding Journal, October 1947.
25. *Engineering Symposium of Future Control of Resistance-Welding Machines*, C. E. Smith, The Welding Journal, October 1947.
26. *Maintenance of Resistance Welding Equipment*, F. R. Woodward, The Welding Journal, April 1948.
27. *D.-C. Resistance Welding Utilizing Kinetic Energy Storage*, Thomas J. Crawford, The Welding Journal, May 1948.
28. *Slope Control and Its Effect on Spot and Projection Welding*, I. W. Johnson, The Welding Journal Res. Suppl., October 1949.

CHAPTER 16

SPOT, SEAM AND PROJECTION WELDING*

FUNDAMENTALS OF PROCESSES

Definition and General Description

SPOT, ROLL-SPOT, seam and projection welding comprise that group of the resistance-welding processes wherein the required heat, at the joints to be welded, is generated by the resistance offered through the work parts to the relatively short time flow of low-voltage, high-density electric current. Force is always applied before, during and after the application of current to assure a continuous electrical circuit and to forge the heated parts together. The maximum temperature achieved is ordinarily above the melting point of the base metal. Equipment and controls employed to achieve these ends are described in Chapter 15. The standard definitions for these processes are:

Spot Welding.—A resistance-welding process wherein coalescence is produced by the heat obtained from resistance to the flow of electric current through the work parts held together under pressure by electrodes. The size and shape of the individually formed welds are limited primarily by the size and contour of the electrodes.

Roll-Spot Welding.—The making of separated spot welds with circular electrodes.

Seam Welding.—A resistance-welding process wherein coalescence is produced by the heat obtained from resistance to the flow of electric current through the work parts held together under pressure by circular electrodes. The resulting weld is a series of overlapping spot welds made progressively along a joint by rotating the electrodes.

Projection Welding.—A resistance-welding process wherein coalescence is produced by the heat obtained from resistance to the flow of electric current through the work parts held together under pressure by electrodes. The resulting welds are localized at predetermined points by the design of the parts to be welded. The localization is usually accomplished by projections, embossments or intersections.

The important distinction between spot and seam welding is that in spot welding the electrodes are retracted after each individual weld or simultaneously completed group of welds, but in seam welding at least one rotating electrode is against the work under continuous pressure making a continuous weld. Seam welds are also less efficiently produced by making tangent or overlapping spot welds with a spot-welding machine.

Spot welds may be made with a seam-welding machine by suitably adjusting the speed of the circular electrode and current interruptions. When this is done the procedure is known as roll-spot welding. Spot welds may also be made by individually retracting the seam-welding electrodes after each weld.

Projection welds are made by localizing the welding pressure, welding current and heating during welding at one or more predetermined points by the configuration or design of one or more of the parts being welded, instead of by the use of pointed or domed electrodes, as in spot welding. Machines and controls identical to those employed for spot or seam welding are used.

Characteristic differences between the spot, seam and projection-welding processes are shown in Fig. 1.

Spot, roll-spot and seam welds may be made on thicknesses as low as 0.001 inch. Spot welding may be used on joints having members as thick as 1 in., although

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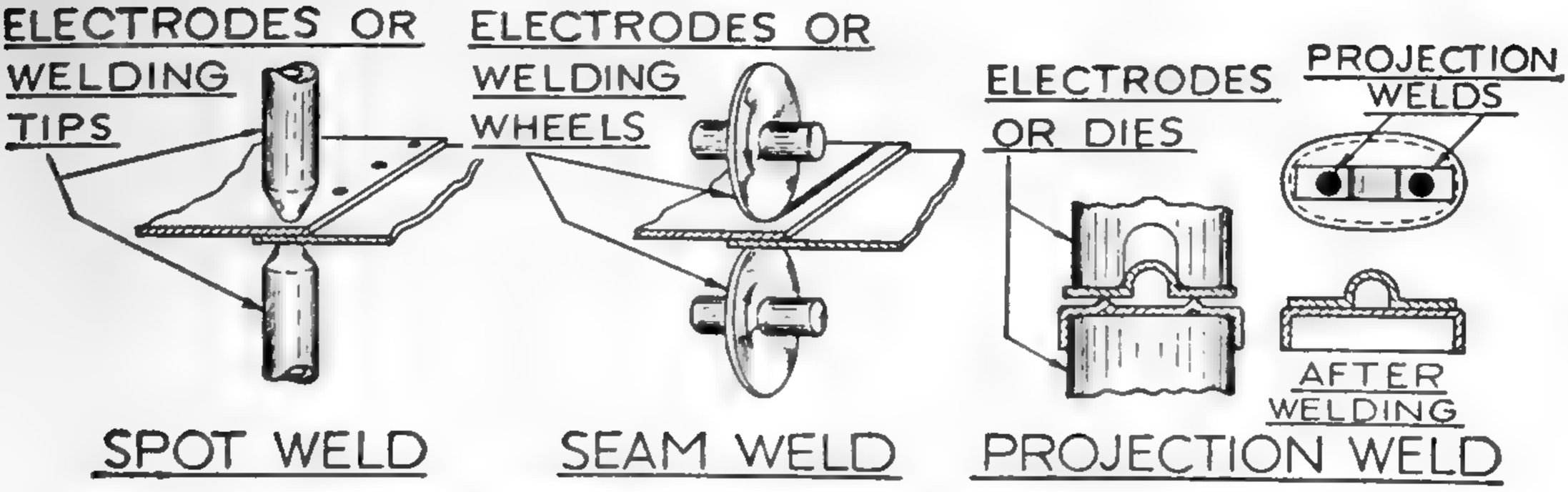


Fig. 1.—Comparison of Spot, Seam and Projection Welding

the bulk of all spot welding is done on thicknesses less than 1/4 inch. Seam welding is most commonly done on thicknesses less than 1/8 inch. Projection welding is best suited for thicknesses 0.02 in. and up. All materials require precise control for production of uniform welds.

Current

Five types of current are used: (*a*) a.c., (*b*) d.c., (*c*) stored energy, a.c. damped oscillation, (*d*) stored energy, d.c. surge and (*e*) stored energy d.c.

Alternating Current.—Alternating current is employed in about 90% of commercial installations. An alternating electric current of several hundred amperes for thin parts and more than 100,000 amp. for heavy parts, is used, depending specifically upon the materials welded and the time and force magnitudes. These currents may be obtained, from well-designed resistance-welding machines, with as low as 1 and seldom more than 30 secondary volts. It is the function of the welding transformer to convert the available commercial voltage, low-current power to the required low-voltage, high-current power. The general manner of making this conversion is shown in Fig. 2. Frequencies of 60 cycles per sec. are most commonly used; other frequencies are used to suit the desired conditions. When designating welding times in terms of cycles, the frequency therefore should always be given.

The magnitude of the nominal peak current and of the zero current time between successive one-half cycles can be fully controlled by synchronous phase shift heat controls, as described in Chapter 15, so that the point of current application and termination, with respect to the voltage wave, will always be the same for successive welds. With non-synchronous controls this point of current application will change for successive welds, resulting in variations in current magnitudes.

In addition to the commonly used single-phase, alternating-current system a method is used wherein an equal amount of current is taken from each of the three phases of the power system, and this three-phase alternating current is converted into direct current which is then reconverted into low-frequency (3 to 25 cycles per sec.), single-phase alternating current. This reconverted current is then fed into the welding transformer.

Direct Current (Constant Magnitude)—Constant magnitude, direct-current welding is accomplished by using a dry disc rectifier, homopolar generator or storage batteries.

Stored Energy, A.C. Damped Oscillation.—With this variation, only one polarity of an alternating-current sine-type wave is employed, the other polarity being damped out. Capacitor discharge controls provide the current wave form.

Stored Energy, D.C. Surge from Capaci-

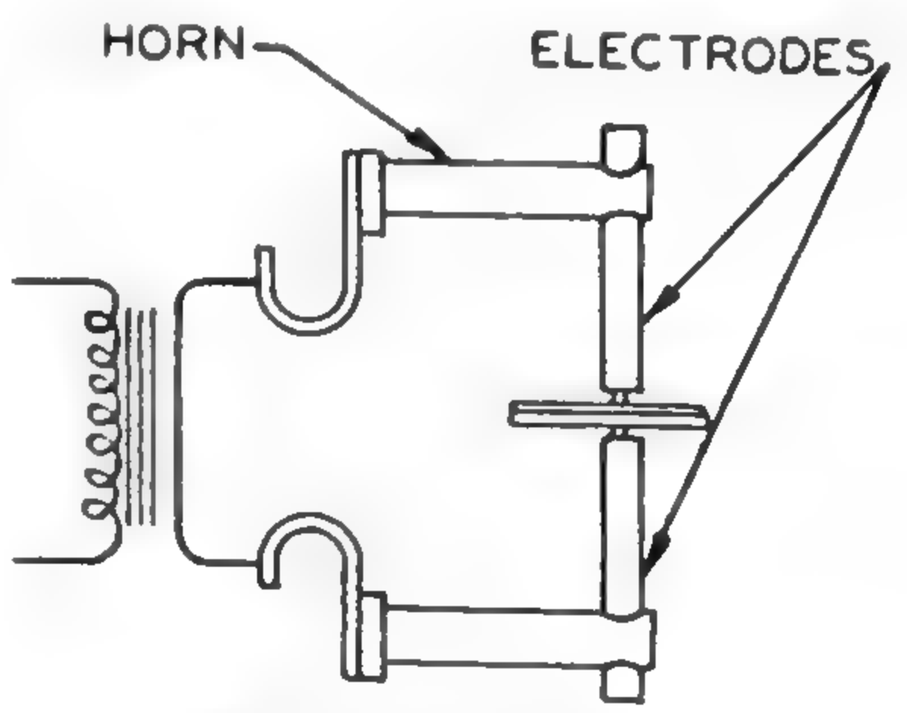


Fig. 2.—Sketch of Spot Welding Circuit

tors.—The direct-current, surge-type of curent involves the charging and subsequent discharge of a series of capacitors through the welding transformer. The welding current delivered by energy storage equipment is generally in the form of a single directional pulse which may alternate from plus to minus polarity. This pulse applies heat to the weld continuously throughout the time of its formation.

Stored Energy, D.C. Surge from Collapse of Magnetic Field.—The energy stored in an electromagnetic system is kinetic. It is not possible to maintain the accumulated energy in a static condition.

Stored Energy, D.C., from Storage Batteries.—This direct-current, stored-energy system of welding is essentially identical to that of direct-current welding, using storage batteries as a source of energy.

Time

The times of current application, hereinafter referred to as *time* or *weld time*, for both alternating and direct currents of the non-surge types are controlled and varied by electronic, mechanical, manual or pneumatic means. Times commonly ranging down to one-half cycle of 60 cycle frequency are used for the thinnest sheets and as long as several seconds for thicker plates, depending somewhat upon the metal being welded. For the capacitor and magnetic types of stored energy systems, the weld time is determined by the electrical constant of the system. Welding currents are varied not only in length of total interval from start of welding current to end of welding current, but also in the order of their application, as shown in Fig. 3.

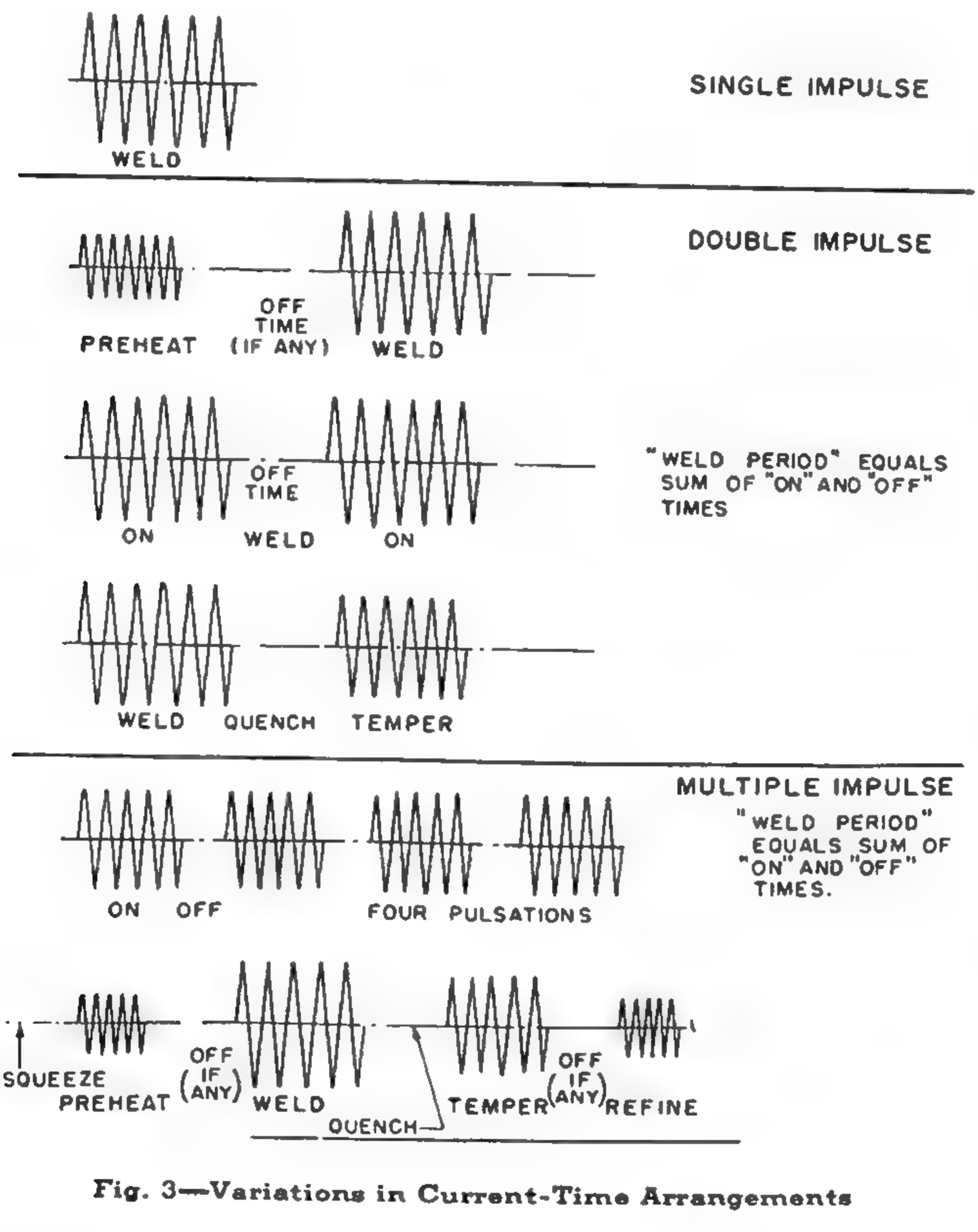


Fig. 3—Variations in Current-Time Arrangements

Single Impulse.—When one single, con-

tinuous application of current is used for the making of an individual weld it is called single impulse welding.

Double Impulse.—When two distinct impulses of current are used it is called double impulse welding. The first impulse may be of a lower current magnitude for preheating or reducing the surface resistance, and the second of higher magnitude for furnishing the welding heat, the intervening off time being short; or both impulses may have the same current magnitude with the off time being short to provide sufficient total time for developing the required welding heat. The first impulse may be the high magnitude welding current and the second impulse of a lesser current magnitude, applied after a suitable cool time interval, to temper the weld made by the first impulse.

Multiple Impulse.—Multiple impulse welding consists of more than two applications of current, each of which flows for a duration of one-half or more cycles separated by an off-period of predetermined amount. This timing may be used for welding in several ways.

A series of on-off impulses of current of the same magnitudes and of one-half or more cycles' duration each may be employed to slowly build up the required welding temperature. This is referred to as *pulsation* welding when applied to spot or projection welding and as *interrupted timing* when applied to seam welding.

A series of on-off impulses of current of selective varied levels and lengths may be used, the functions of each successive level being to preheat the material, to form the weld, to temper the quenched structure and lastly, if desired, to refine the grain structure; or any two of these functions in addition to the second may be employed.

A continuing sequence of on-off d.c. discharge waves may be used for the making of continuous seam welds.

There are two important time intervals in addition to the total interval between the first initiation and final termination of welding current. The period before the initial current application, or the *squeeze time*, is the interval between the instant the electrode contacts the work and the initial application of the current. A finite interval is required because the pressure is not instantaneously built up to its required value. The second time interval occurs between the final current termination and the instant of pressure release from the electrodes. This interval, known as *hold time*, is required to permit solidification of the weld ingot under pressure. If the current is inadvertently applied either immediately before the electrodes contact the work or during the electrode retraction, a low-voltage, high-amperage arc will momentarily occur between the electrodes and the work. This will destroy the electrode tip contour and damage the work surface.

Electrode Force.—The electrical circuit between the electrodes and through the work is assured of its completion by the continuous application of a clamping pressure. This pressure is exerted on the work through electrodes using manual, hydraulic, pneumatic or mechanical means. For a given material composition and thickness, the higher the magnitude of the applied force the more it serves to:

(*a*) Bring the various interfaces into intimate contact.
(*b*) Reduce initial contact resistance between the interfaces and between the exterior surfaces and the contacting electrodes.
(*c*) Require and permit the use of higher secondary currents.
(*d*) Reduce porosity and internal ingot cracking.

The force throughout the squeeze, weld and hold times may be applied in several magnitudes:

1. A constant single force throughout.
2. A double force magnitude with a high initial value for reducing initial contact resistance and for bringing the parts into intimate contact ((*a*) and (*b*) above), followed by a lesser force for welding, to reduce (*c*) above.
3. A triple force magnitude being the same as (2) followed by re-application of an equal or even higher force near the end of the current flow to accomplish (*d*) above.
4. A double force magnitude with the current applied at a suitably low pressure followed by a higher pressure near termination of current flow to reduce (*c*) and achieve (*d*) above.

There are practical limits to each of these possibilities. For example, the use of insufficient pressure during welding will result in high contact resistance, causing excessive surface heating even with

currents insufficiently high to form satisfactory welds.

Elcctrodes

Resistance welding electrodes perform four functions:

1. They conduct the total welding current to the work, and determine the current density in the weld zone.
2. They transmit the force to the weld area and determine the pressure in the weld zone.
3. They dissipate the heat from the weld zone, thus preventing surface fusion of the work.
4. They maintain alignment of the work and often act as work locators in projection welding.

The first of these functions is electrical. If the application of pressure was not involved for mechanical reasons, suitable electrode selection could be made almost entirely on the basis of electrical and thermal conductivity, taking into account the resistance of the electrode itself and the resistance at the area of contact between the electrode and the work surface. The second function is mechanical. During welding operations the electrodes are subjected to stresses which are often of considerable magnitude, and they must withstand these stresses at elevated temperatures without excessive deformation. Proper electrode shape maintenance is important because the current not only must be conducted to the work, but also must be localized within a fixed area. The transmitted pressure forges the heated work-pieces together, and restricts the passage of welding current to a fixed area.

Successful execution of any resistance-welding operation, however simple or complicated it may be, is dependent upon the proper functioning of the electrodes. Recent developments have made it more evident than ever before that good resistance welding requires precision. The welding equipment is designed to furnish the electrical system, mechanical system and the sequencing of each. It becomes the overall function of the electrodes to conduct the current and to withstand the high pressures, so as to maintain a uniform contact area and to insure the continued proper relationship between correctly selected current and pressure. Uniform contacting areas should therefore be maintained.

When a single spot or seam weld is to be made at one time, only one pair of electrodes is used. In this case the full magnitude of the force and current is applied by shaped electrodes to the individual weld being made. Only one pair of electrodes need be used for making several closely spaced projection welds.

Principles of Operation

General.—The operations of spot, roll-spot, seam and projection welding involve a coordinated application of current of the proper magnitude for the correct length of time. This current must pass through a closed circuit, assured of its continuity by forces applied to the electrodes, which are shaped to provide the necessary current and pressure densities. The entire sequence of operations is required to develop sufficient heat to raise a confined volume of metal to or above its melting point and to then resolidify and cool this metal, under pressure, to a temperature where it has adequate strength to hold the parts together. The achieved temperature must be such that fusion or incipient fusion is obtained, but not so high that molten metal will be forced from the weld zone. Both the rate of rise and fall of temperature must be sufficiently rapid to assure the achievement of commercial welding speeds but neither must be permitted to be so rapid that either inconsistent or brittle welds will be produced. The rate of rise and fall of temperature and the time of maintenance at temperature are determined by the characteristics of the metals being welded and by the capacity of available equipment.

The heat required for any resistance-welding process is produced by the resistance offered to the passage of an electric current through the work-pieces in exactly the same manner as any other electrical heating device. Since the ohmic resistance of any resistance weld is low, high welding currents are required to develop the necessary welding heat.

The rate of heat generation depends upon the flow of current in amperes through the resistance offered by the material. Other electrical factors, such as voltage, frequency and power factor enter into consideration only with respect to their uniformity, and only affect the value of the current.

Ohm's Law, one of the basic electrical theories, states that:

$$I = \frac{E}{R} \quad \text{or} \quad R = \frac{E}{I}$$

where I is current in amperes, E is the emf. or voltage drop across the electrodes, and R is the resistance through the material in ohms. R is the summation of the contact resistances and the resistance of the work to be welded. Therefore, for a given value of R, the magnitude of I is determined by E. Current regulators provided on most welding machines merely control the secondary voltage, which, in turn, determines the current delivered to the weld of a given resistance.

The total heat in watt-seconds generated in the work being welded and in the welding electrodes is expressed by the formula

$$H = I^2RT,$$

where T is time in seconds. From the heat and current equations it also can be shown that

$$H = IET$$

Mechanical Characteristics.—The mechanical operation of spot, seam and projection-welding machines is essentially the same. The electrodes approach and retract from the work at properly controlled times and rates, and the clamping force of the electrodes is applied in the meantime by manual, pneumatic, hydraulic or mechanical means. Rate of electrode approach must be rapid but controlled so that the electrode faces are not hammered out of shape. The locally heated workparts both expand and contract during the welding operation and the electrodes, under pressure, are in dynamic motion. The rate of change of motion is influenced by the weight of moving parts or inertia and by friction between the moving and fixed parts. Under these conditions adequate pressures must be maintained.

Two parallel conductors carrying current in opposite directions, as in Fig. 2, are mutually repelled. This repelling force is trying to push the electrodes apart. To prevent the electrodes from actually leaving the work, the total force applied must be greater than the repelling force. In addition this force must be sufficient to compress the work parts together when they become molten or plastic. For example in a projection weld if the height of the embossment is 0.025 in., and it is desired to weld the two pieces flush in one cycle and if the actual time the metals are plastic is approximately one-half of the total time the current is applied, or $^1/_{120}$ sec., the net force available for accelerating the electrodes during the $^1/_{120}$ sec. must be sufficient to cause the electrode to travel 0.025 in., the height of the embossment. The accelerating force, together with the momentum of the head weight itself, must not be so high as to deform the contacting tips of the electrodes, or flatten and crush the parts to be welded, therefore preventing the satisfactory use of the desirable short time.

When the electrodes do not follow through as fast as the materials melt, excessive surface heating may occur and an arc may form between the electrodes and the work. This arc burns or pits the electrode faces and causes them to stick. If the delay is long enough, the parts being welded may vaporize from the additional heat due to the increased resistance caused by the low electrode pressure. This may happen with explosive violence. The condition is greatly aggravated in some metals, such as brass or aluminum, where the temperature range involved when they change from the solid to liquid or from liquid to vapor state is very short.

For the reasons illustrated, high speed follow-up, low-inertia head machines have been developed and are available for the welding of such nonferrous metals as aluminum and brass. A properly designed lower arm of adequate rigidity to prevent deflection which would result in lateral electrode skidding should also be employed in a low inertia unit.

Electrical Characteristics.—Sufficient voltage must be available in the electrical system to provide the required rms. current at the work to produce a weld of desired size (strength). The voltage necessary to produce this required current is determined entirely by the geometry of the secondary circuit, i.e., the size of the secondary loop and the amount of copper conductor in the circuit. This voltage is referred to as the secondary open-circuit voltage and when multiplied by the welding current (secondary current) gives the demand kva. of the welding transformer. The output or demand rating (kva.) of a welding transformer is usually many times its thermal rating, since the welding current flows for a small part of the total time. The duty cycle of a transformer

is defined as the percentage of time the transformer is actually carrying current and may be expressed by the following formula:

$$\% \text{ Duty cycle} = 100 \times \frac{\text{Current On time}}{\text{Current On time} + \text{Current Off time}}$$

It is standard practice to rate welding transformers on a 50% duty cycle, i.e., a 100-kva. transformer can carry a 100-kva. load for 30 min. out of each hour. It is often necessary to find the permissible kva. output of a welding transformer while operating at a certain duty cycle, or to find the permissible duty cycle at which a welding transformer can operate while supplying a known kva. demand. These can both be easily found with the use of the curve shown in Fig. 4 which gives the percent load allowable at various duty cycles.

The following general principles may be stated:

1. With a given secondary voltage the welding current will decrease as the throat depth is increased (Fig. 2).
2. The power factor (cosine of angle *a*, Fig. 5) will usually decrease with increasing throat depth and throat gap. The effect of the latter is greater.
3. With the welding of increasingly heavier materials which do not extend into the throat, the reactance is not appreciably changed but the resistance increases and the power factor increases.
4. Since the reactive current is in-

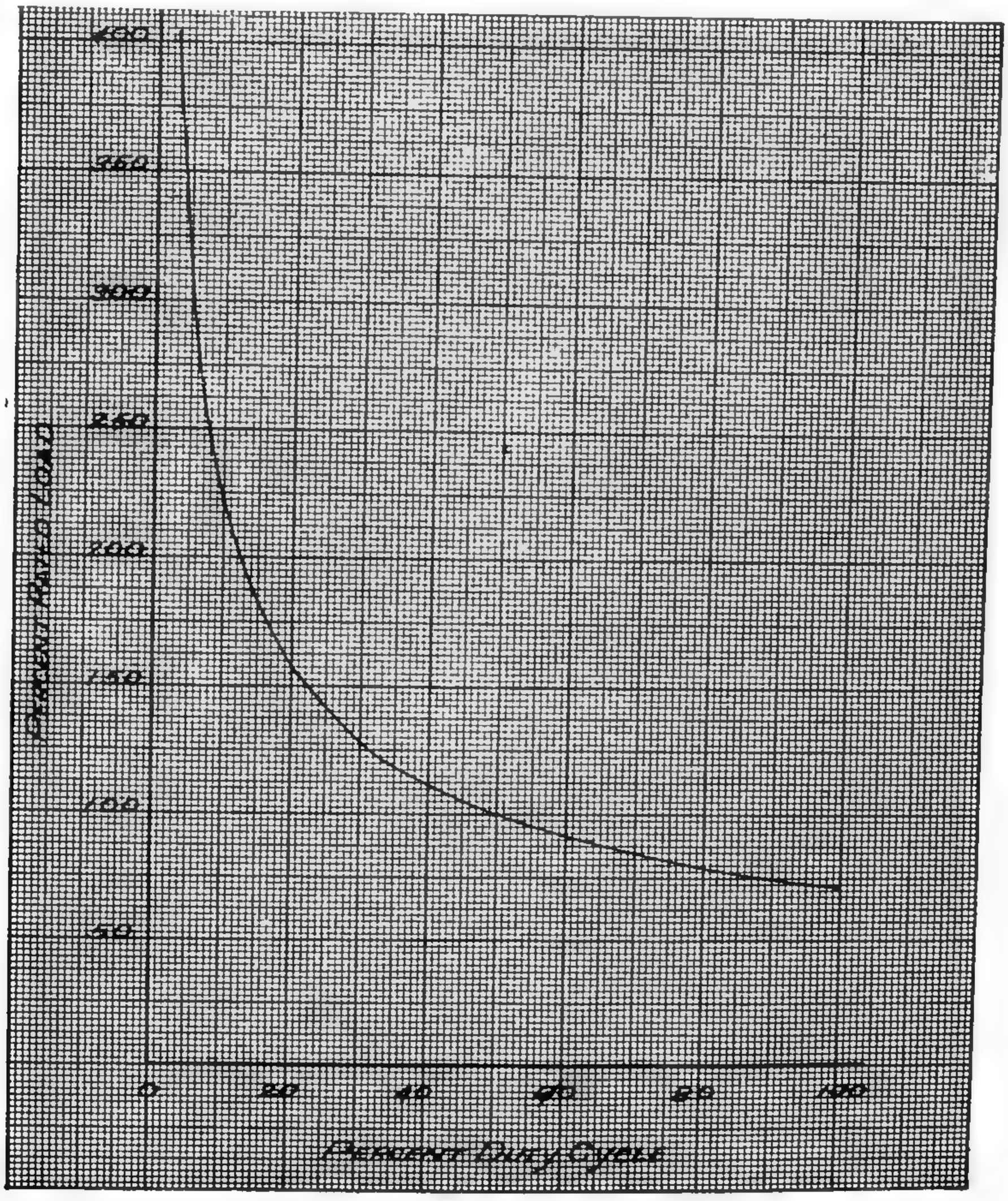


Fig. 4—Operating Duty Cycle Vs. Percent Nameplate Rating

versely proportional to the frequency, the impedance of the secondary circuit is considerably less on 25 cycles than on 60 cycles.

5. Consequently, for a given secondary current, less secondary voltage is required on 25 cycles than on 60 cycles. Since the primary demand in kva. is proportional to the square of the secondary voltage, considerably less kva. is required.

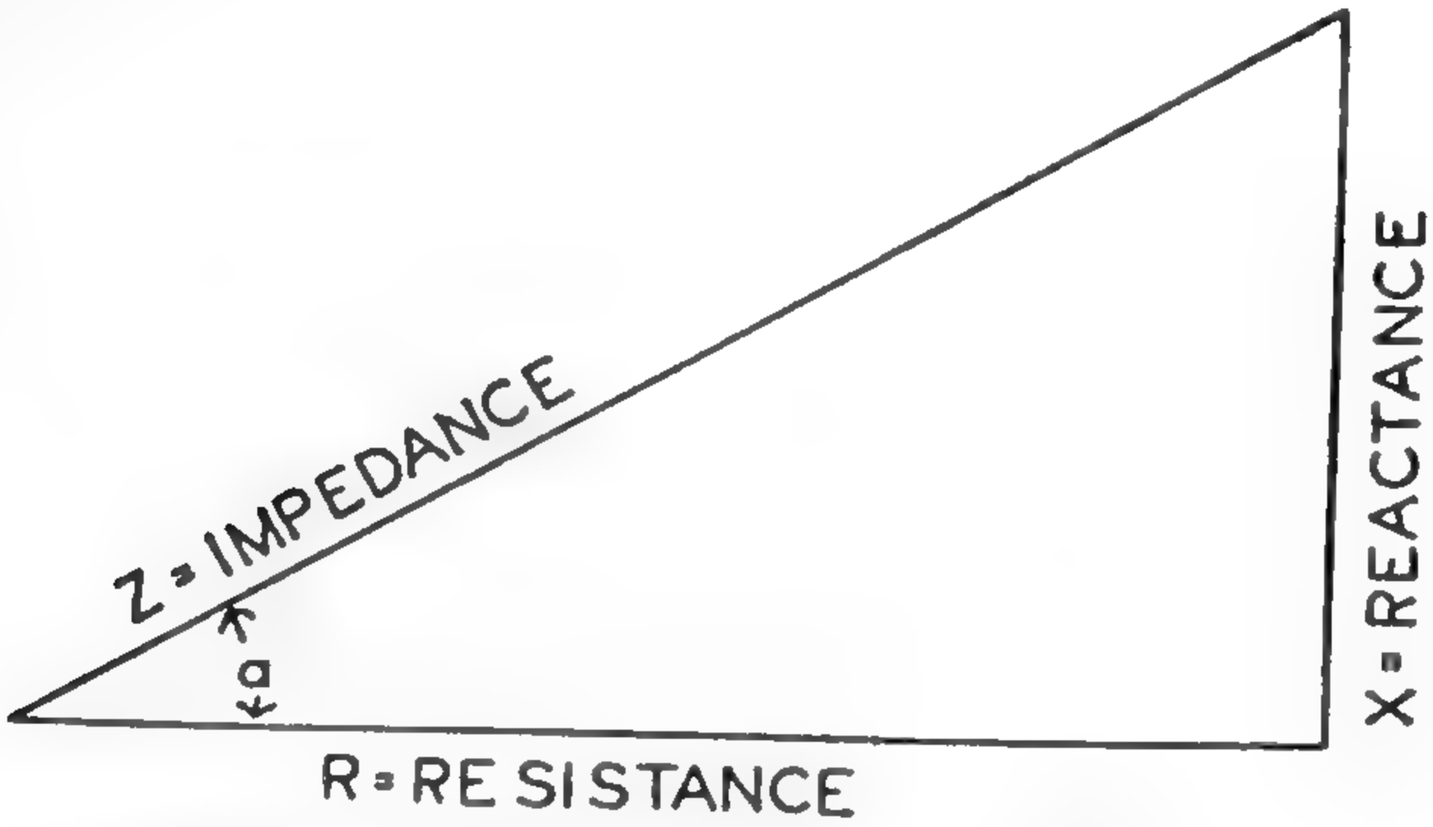


Fig. 5.—Relationship Between Resistance, Reactance and Impedance

This reduction in kva. demand will amount to 25 to 50%, depending upon the geometry of the machine and the work. However, the values may be considerably different for some portable machines.

Power Requirements.—Power demand from the line is a function of the type of current and equipment employed. An adequate power supply is one of the requisites of present-day, high-production resistance welding. Every welding engineer should recognize this fact so that, even though he is not able to solve the power-supply problem, he will be sure to bring it to the attention of those whose responsibility it is to provide an adequate power supply.

It is the high kva., intermittent *on time* and low power factor of single-phase, a.c. welding machines which create serious power problems. Because of this fact the energy storage, frequency converter and dry disc rectifier types of machine and series capacitors, Scott-connected autotransformers and various other arrangements for use with single-phase a.c. have been devised. Nevertheless, because of their lower cost, wider adaptability and relative simplicity, over 90% of all resistance-welding machines built in the past are single-phase, a.c. machines.

In general the source of power supply should be adequate and stable to the extent that variations in power supply voltage do not vary more than plus or minus 5% due to loads other than from the machine in question. Where adequate power supply is not available the use of one of the stored energy types of machine is indicated. The importance of providing constant voltage and current to the primary of the welding transformer is to assure that uniformity of secondary current is obtained at the weld.

Heat Generation.—The secondary circuit of a resistance-welding machine, including the work being welded, is considered as a series of resistances, the arithmetical total of which in each circuit affects the flow of current. The current flow in amperes must be the same in all parts of each circuit regardless of the resistance at any point in the circuit, but the heat generation at any point will be directly proportional to the resistance at that point. Thus, it is possible to design an electrical circuit to produce heat exactly where it is wanted, leaving the connecting parts of the same circuit relatively cool.

An important characteristic of resistance welding is the rapidity with which this heat can be produced. The composite effects of heat generated and lost in that part of the secondary circuit embracing the work and electrode tips is illustrated in Fig. 6. There are in effect at least seven resistances connected in series for any one weld and there are

more for multiple thickness joints. For a two-thickness joint these are:

1. Upper electrode.
2. Contact between upper electrode and upper sheet.
3. Body of upper sheet.
4. Contact between upper and lower sheets (interfaces).
5. Body of lower sheet.
6. Contact between lower sheet and lower electrode.
7. Lower electrode.

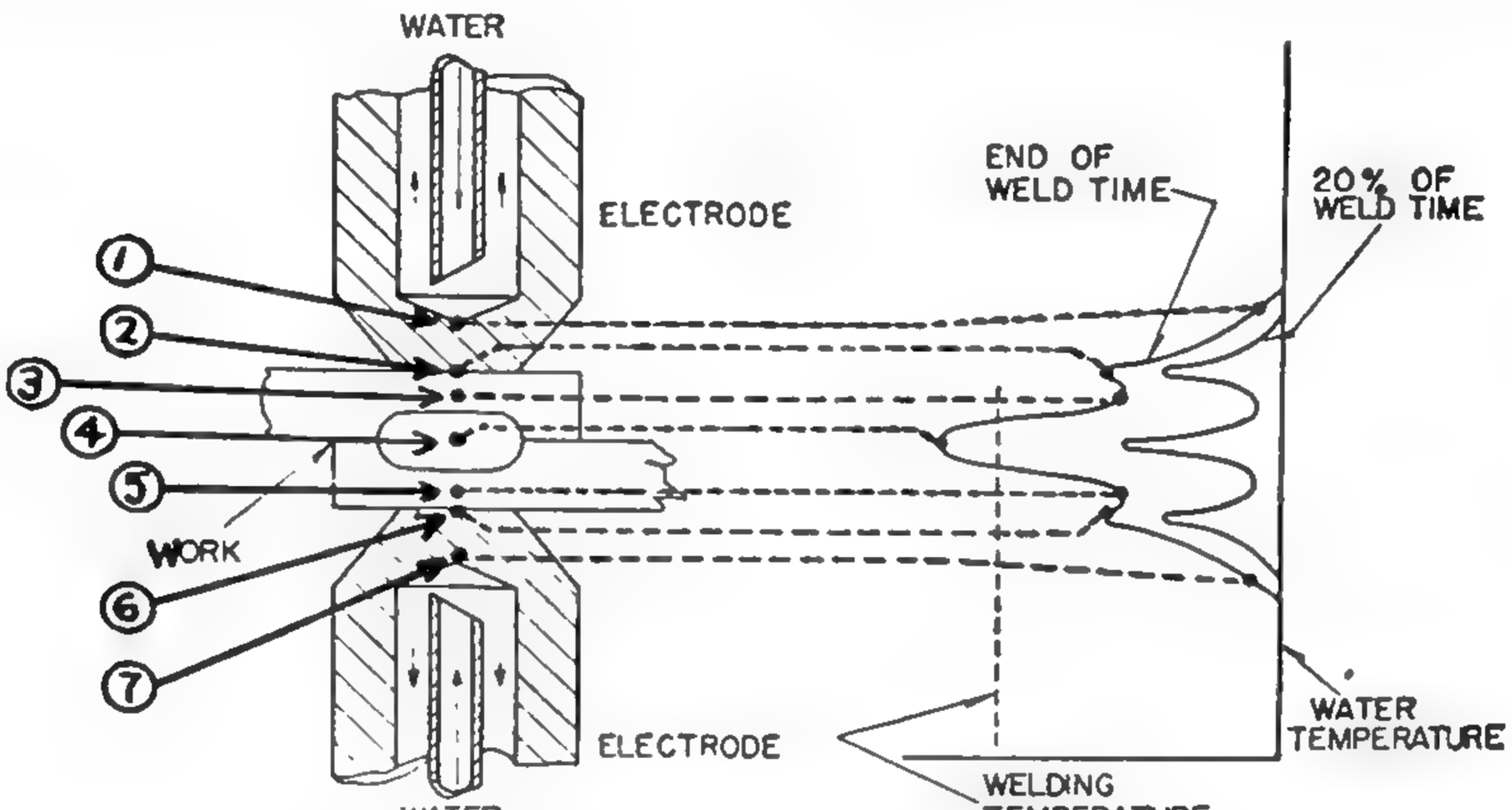


Fig. 6.—Temperature Distribution in Spot Welding

Not all of the heat is generated at the proper point, that is, the juncture of the work parts. The flow of heat to or from this point, which in turn assists or retards the creation of the proper localized welding heat, is governed by the temperature gradient established by the welding current acting on the various resistive components.

Heat will be generated in each of the seven sections in Fig. 6 in proportion to the resistance of each. However, welding heat is required only on plane *4*, and efforts must be made to reduce the heat as much as posible at all other points. At the start of a weld the temperature at all parts is represented by the vertical line marked *Water Temperature*. The greatest resistance is at plane *4;* therefore, heat is most rapidly developed at that location. Points of next greatest resistance are *2* and *6*, and the temperature rises rapidly at these points also, but not as fast as at plane *4*. After a low percentage of the total time allowed for the weld, the heat gradient probably corresponds to the right-hand jagged line. Heat generated at *2* and *6* is rapidly dissipated into the contacting liquid-cooled electrodes *1* and *7*, whereas the heat at *4* is partially trapped and dissipation is much slower. Therefore, as the weld time progresses, the rate of rise for plane *4* will be much more rapid than for *2* or *6*. The welding temperature is indicated by the vertical dotted line. In a perfectly controlled weld the welding temperature would first be reached by pin points on the interfaces, and then grow into a nugget as time progresses.

Factors affecting the amount of heat being produced in the weld by a given current for a unit of time are:

1. The electrical resistance of the materials being welded.
2. The electrical resistance of the electrode materials.
3. The contact resistance between work parts as determined by surface conditions, scale, welding pressure, etc.
4. The contact resistance between the electrodes and the work parts as determined by surface conditions, area of electrode contact and welding pressure.

Influence of Current.—In the heat formula, $H = I^2RT$, current is a squared quantity, hence has the greatest effect on the generation of heat. It is therefore the variable which must be most carefully controlled. Some of the factors which cause variation in secondary current are: fluctuations in line voltage and variations in secondary impedance caused, in the case of a.c. machines, by variations in geometry of the throat and the introduction of varying amounts of magnetic materials into the secondary loop of the machine.

In addition to variations in magnitudes of delivered current, variations in current density are produced at the weld interface by shunting of current through preceding welds and through metallic contact at points other than between the clamping electrodes as shown in Fig. 7. Mushroomed or oversized electrodes also result in reduction of welding heat and weld properties through reductions in current density.

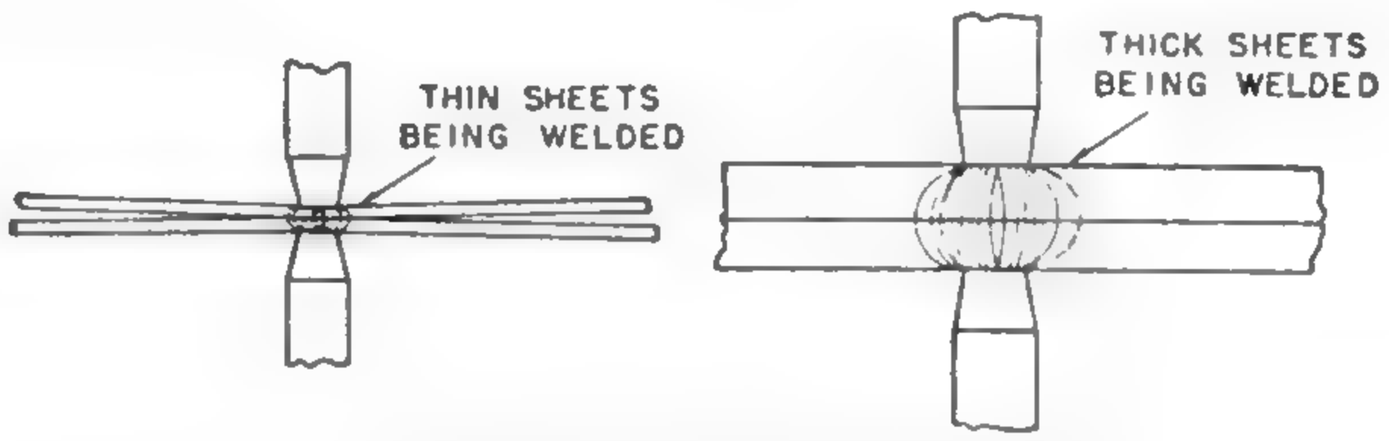


Fig. 7.—Current Distribution in Spot Welding

For all conditions, a finite amount of current is required before any weld is formed but once incipient fusion temperature is reached the weld nugget size and strength increase rapidly with slight further increases in current. Excessive amounts of current result in weld expulsion, cavitation, weld cracking and reduced mechanical properties. Typical variations in shear strength of a spot weld as a function of current magnitude are shown in Fig. 8.

Influence of Time.—The rate of heat generation must be such that the welding will be achieved in the required interval with proper compensation for heat losses. The total heat developed is a linear function of time. The losses are caused by conduction into the surrounding work parts and into the electrodes, and also by radiation from the work parts into the surrounding air. These losses are essentially non-controllable, except that they increase with increases in total time.

In the heat gradient curve, in Fig. 6, time moves to the left from the starting point (black vertical line). If the time is continued beyond that shown in the figure, the temperature of plane *4* will exceed the melting point, and at some points pass the boiling point of the work-pieces, causing gas pockets, which may result in expulsion of minute particles, or *spitting*. If the contact planes *2* and *6* are scaly or pitted, the same thing may happen there. A continued application of current will cause the peaks to be less pronounced, the nugget will grow completely to the electrode faces, and volumes *3* and *5* will become plastic, which may result in severe embedding of the electrodes, particularly for high face angles. Furthermore, the heat-affected zone will extend far into the sheets beyond the electrodes. Finite values of time are required before any weld nugget is formed, the exact minimum length depending upon current magnitudes and material thickness and composition. In most cases, at some period during an extended welding interval, the radiation losses will equal the heat input, thus stopping further temperature rise. An illustrative relation between weld time and spot weld shear strength is shown in Fig. 9.

Since the heat generated is proportional to the square of the current, if losses are neglected, doubling the current will quadruple the heat developed over any period of time. To a certain extent, time and current may be complementary, that is, a desired change of total heat may be secured either by a change of current or by a change of time. However, heat trans-

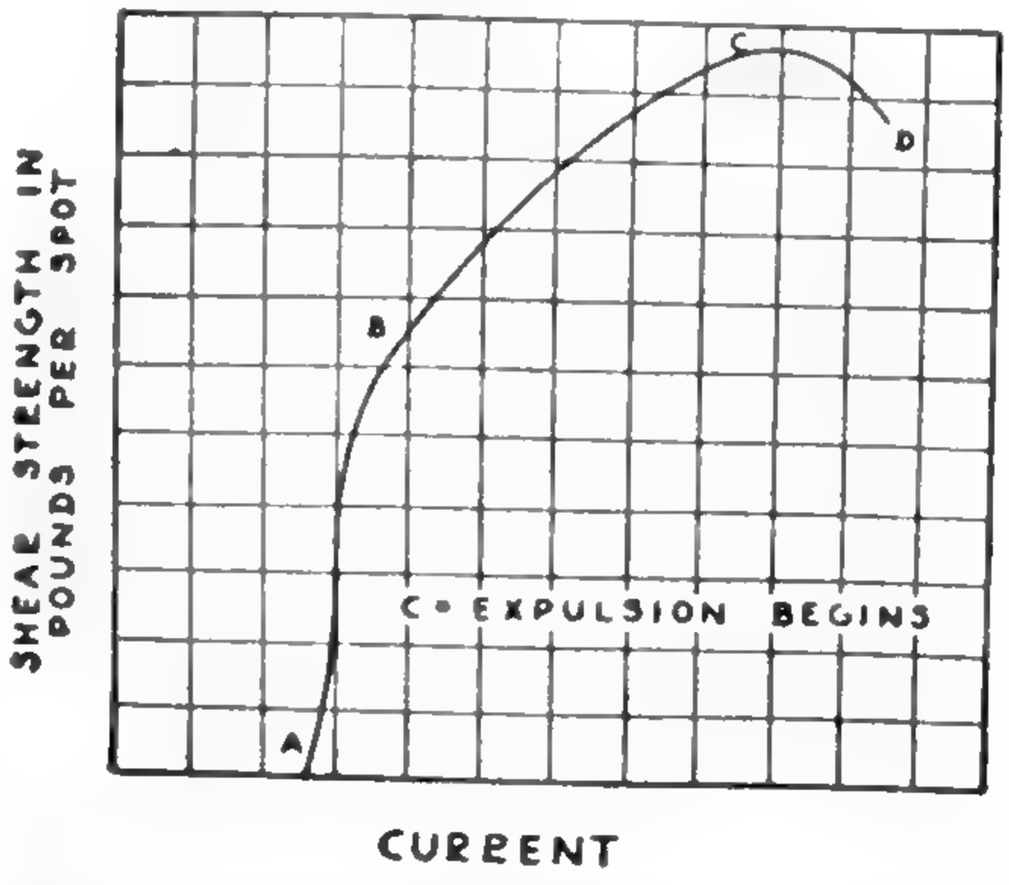


Fig. 8.—Influence of Current on Spot Weld Shear Strength in Material Over 1/16-In. Thick

fer is a function of time, and in the development of the proper nugget size the time element cannot be shortened too much regardless of the increase in current. The first effects of insufficient timing are noticed when heat is generated too rapidly at the contacting surfaces, resulting in pitting and spitting, especially at the electrode contacting surfaces.

When spot welding heavy plates, the current is commonly applied in several relatively short impulses or pulsations without removing electrode pressure. Again referring to the heat gradient, Fig. 6, the cumulative results of these several impulses can be observed. It is desired to build up the central peak and retard the electrode face peaks. A continuation of impulses causes a more rapid rise at this central peak than at the electrode faces, provided proper heat balance is achieved. This is aided by the quenching action of the high conductivity electrode material.

Influence of Net Welding Force and Pressure.—The variable, R, in the heat equation is influenced by electrode pressure through its effect on contact resistance. Force is considered to be the net dynamic force of the electrodes upon the work, and it is the resultant pressure which varies the resistance.

The work-piece being spot, seam or projection welded must be held together at the weld area to enable the passage of the current. The amount of this pressure determines, to some extent, the total resistance between the electrodes and therefore the amount of current flowing through the weld. Everything else being the same, as the pressure is increased the current also increases and vice-versa. However, the effect on the total heat generated may also be the reverse, because as the pressure is increased the contacting surface resistance is decreased, often necessitating an increase in secondary voltage to provide more current to compensate for the reduced resistance.

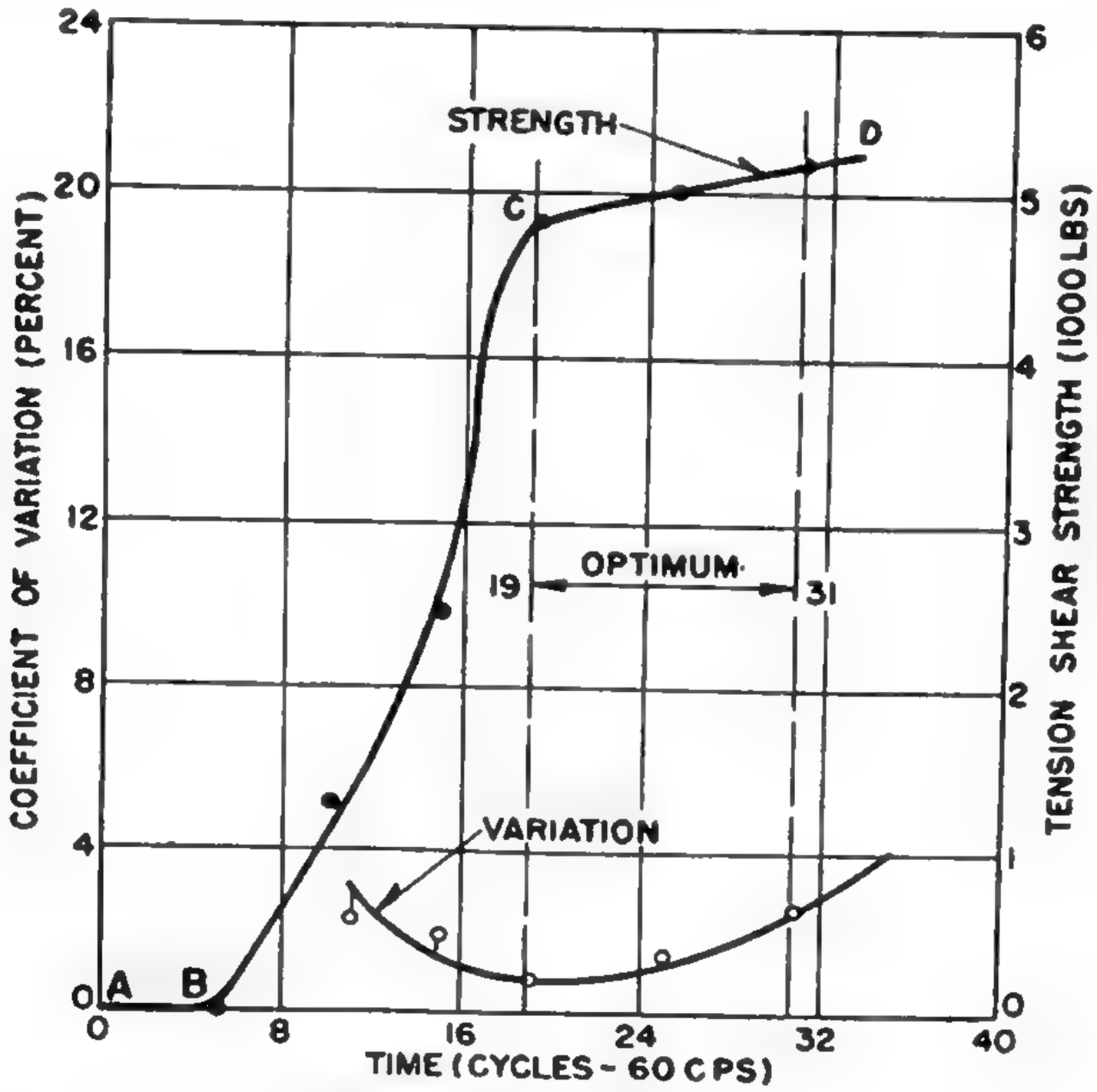


Fig. 9.—Relationship Between Weld Time and Spot Weld Shear Strength

Most of the secondary impedance is made up of the larger reactance and resistance components of the machine. The resistance of the work is a small percentage of the whole in magnitude and still smaller in vector sum. Hence, pressure changes have small effect on impedance and, therefore, on the welding current. This is illustrated by the relatively small effect of pressure variations on heat generated, since the I^2 quantity is little affected and R is the only quantity manifesting this change of pressure.

If the surfaces of metal sheets are

highly magnified they appear somewhat like a washboard or choppy body of water. When subjected to light pressure, the actual metal-to-metal contact may be only a small percentage of the nominal area of contacting surface. As the pressure is increased these high spots are depressed, increasing the actual metal-to-metal contact, thus decreasing the contact resistance. The ideal solution would be to control the force exerted at the interfaces and the force exerted at the outside surfaces of the sheets separately. This is achieved in projection welding. Except for a few applications, the electrode material is softer than the work-pieces, consequently the application of a given force may result in better contact at the electrode contacting surfaces than at the interfaces.

Standard welding machines are provided with sufficient adjustment to cover a wide range of both force and current control. These ranges are balanced as dictated by sound engineering and economic and commercial practice.

When the electrodes are slow in following any sudden decrease of total work thickness, a momentary reduction in pressure will occur. The usual cause of a sudden lessening in work thickness is weld overheating and possibly an expulsion of metal. Rapid contraction may also occur following current termination in the case of short time welds and thin materials due to their high rate of cooling.

A momentary reduction in pressure while the current is flowing causes increased surface contact resistance, with a resultant increased rate of heat generation. Between the work parts the greater rate of heat generation causes or tends to cause further and more violent expulsion of metal. Beneath the electrode tips the increased heat tends to cause melting of the weld through to the exterior surfaces, pitting and loss of corrosion resistance of the surface, as well as marked reduction in electrode life.

Another consequence of the reduction of applied pressure is the release of molten metal from within the weld. Molten metal is retained by a ring of unfused metal which surrounds the weld nugget at the interfaces by the pressing action of electrode force. A momentary reduction in electrode force permits the internal metal pressure to rupture this surrounding ring of unfused metal.

Too high pressures are likely to cause objectionable distortion.

Influence of Electrodes.—Commercially pure copper is an excellent electrical conductor and was used extensively for resistance welding electrodes until other materials possessing adequate electrical conductivity together with superior mechanical properties became available. With the development of procedures which utilize higher currents, higher pressures and greater welding speeds, the use of copper as an electrode material has been almost discontinued.

The principal difficulty with cold drawn copper is its low resistance to both static and dynamic compressive forces and its low annealing temperature which is evidenced by its *mushrooming*. While the welding current is usually considered in terms of total current in amperes, a closer analysis must consider it in terms of current per unit area of electrode contact. For any given welding conditions, a welding electrode with a specified contact area should be used which will produce a current density in the work of a satisfactory number of amperes per square inch. With continued use of the electrode its face becomes mushroomed, increasing the diameter and consequently its area, which in turn decreases the current density (amperes per square inch).

To overcome these objectionable features of commercially pure copper, there have been developed a number of copper alloys of superior physical and mechanical properties. Generally speaking, the harder the alloy, the greater its electrical and thermal resistance. Therefore, the choice of the proper alloy for any application is governed by a consideration of its electrical and thermal properties vs. its mechanical qualities. For instance, electrodes for aluminum welding will have high conductivity at the expense of high compressive strength. Electrodes for welding stainless steel on the other hand, sacrifice high conductivity to obtain maximum compressive strength.

Resistance to mushrooming depends on the proportional limit and the hardness of the copper base alloys; the proportional limit is largely a matter of heat treatment. The temperature of the body of the electrode is relatively unimportant since the governing factor is the temperature of the contacting surface. This is

where the annealing and mushrooming take place.

Size and shape of electrodes are usually determined by the size and shape of work to be welded. For ordinary work, spot and seam welding electrodes should be either domed or flat faced with low angles of face taper, and of sufficient size to adequately carry their electrical, thermal and mechanical loads.

Influence of Surface Condition.—The surface conditions of the parts being welded influence the heat generation through the resistance of the contacting surfaces, *2*, *4* and *6* in Fig. 6. If all of these surfaces are clean the most uniform results will be obtained.

Welding of any kind of material with oxides or scale on the surfaces produces variable and unpredictable results. Scale on the work surfaces also becomes embedded in the electrode faces causing rapid electrode deterioration. Grease and oil do not cause much difficulty provided they are clean. The greatest trouble from oil and grease is the pickup of dirt, which also causes electrode deterioration.

Influence of Metal Composition.—The specific electric resistivity of a metal directly influences the magnitude of the value R in the heat formula and hence of the temperature for a given current, as shown in Fig. 6. Resistivity is the inverse of conductivity. In high conductivity metals, such as silver and copper, little heat is developed even under high current densities. Since the thermal conductivity of these metals is also high, the little heat generated is rapidly transmitted into the surrounding work and into the impressing electrodes.

The composition of a metal determines its specific heat, melting point, latent heat of fusion, thermal conductivity and density, hence the total amount of heat which must be generated to bring it to its melting point. The amounts of heat necessary to raise unit masses of most commercially available metals to the fusion temperature are very nearly the same. For example, two metals of such widely differing spot-welding characteristics as stainless steel and aluminum require the same Btu.'s per pound to reach fusion temperature. However, the thermal conductivity of aluminum is ten times greater than that of stainless steel. Therefore many more Btu.'s must be generated in the aluminum spot weld than in the stainless steel weld to supply the greater heat losses into the electrodes and surrounding metal. Also, the electrical resistance of aluminum is about one-tenth that of stainless steel, so that, in the heat equation the welding current for aluminum must be considerably greater than for stainless steel.

Much of the difficulty in spot welding molybdenum sheets lies in the high-melting point weld area being so closely adjacent to the current-force transmitting electrodes.

The composition of a metal also influences the temperature range over which it is in the readily molded state. This is the range in temperature between the point of softening and melting. Steel begins to soften at about 1500° F. and actually melts or becomes liquid at about 2200° F. For this reason, the conditions for welding steel are not critical since any given two pieces can be welded over a wide range of current, time and pressure. Aluminum has a very short plastic range and, to secure good results, the welding variables must be closely controlled.

The composition of a metal also affects the temperature range between solidus and liquidus. In this range it is possible to produce plastic fusion welds or recrystallization across the interface. Also composition affects the surface conditions at this plastic range. For example, aluminum or chromium produces an oxide protective film that interferes with welding. In wrought iron the slag acts as a flux at this forging temperature making plastic or solid phase welding easy.

Heat Balance.—If two pieces of equal composition and thickness are welded together with electrodes of equal mass and contour, heat will be generated in both pieces uniformly, and the weld cross section will be of the typical oval shape. When this condition exists, there is a correct heat balance. However, if one of the pieces has a higher electric resistivity than the other, heat will be generated more rapidly in this piece than the other, resulting in a less-than-perfect weld depending upon the amount of heat unbalance. In the case of dissimilar metals, such as when welding plain carbon steel to stainless steel, this dissimilarity can be compensated for by increasing the contacting electrode area on the high-resistivity stainless steel side.

or by using an electrode material of higher resistance on the low-resistivity carbon steel side.

In the case of similar metals of unequal thickness, the same considerations hold true in a general way. For higher ratios of dissimilarity of thickness there is a tendency toward the generation of insufficient heat at the interfaces, because of the proximity of the cooled electrode on the thinner part. Proper heat balance can be achieved by using a smaller contacting electrode area on the thinner side of the joint, with short times and high current densities.

Electrode diameters are usually given for various work thicknesses within a narrow range and if the proper sizes are used for each thickness, the heat balance may be considered as satisfactory.

Heat Dissipation.—In the formula for heat required to reach fusion temperature there is usually a corrective factor for radiation or dissipation of heat from the weld, which continues at a varying rate from the instant of current application until the weld has cooled back to room temperature. A study of heat dissipation should be divided into two phases: during the time of current application, and after the cessation of current flow. The extent of the first phase depends upon the composition of the metal, the mass of pieces, the welding time and the external cooling means. The composition and mass of the work-pieces cannot be controlled, but the external cooling means can.

The heat generated for a given amount of current is inversely proportional to the electrical conductivity. The thermal conductivity determines the rate at which this heat is dissipated or conducted from the weld. These two factors run closely parallel in most metals. In a high conductivity metal, such as copper, the small quantity of heat generated is dissipated at a rapid rate into the surrounding metal and into the electrodes.

If the electrodes remain in contact with the work after current flow ceases, and some hold time must be provided to assure that the current is not flowing at the start of electrode retraction, the weld is rapidly cooled by virtue of the high thermal conductivity of the electrode material. This rapid heat dissipation is aided by efficient liquid cooling of the electrodes. The rate of lateral quenching from the surrounding metal of the parts being welded (see Fig. 10) is reduced if a longer welding time is employed, since this procedure allows more heat to transfer into the surrounding metal raising its temperature and reducing the tem-

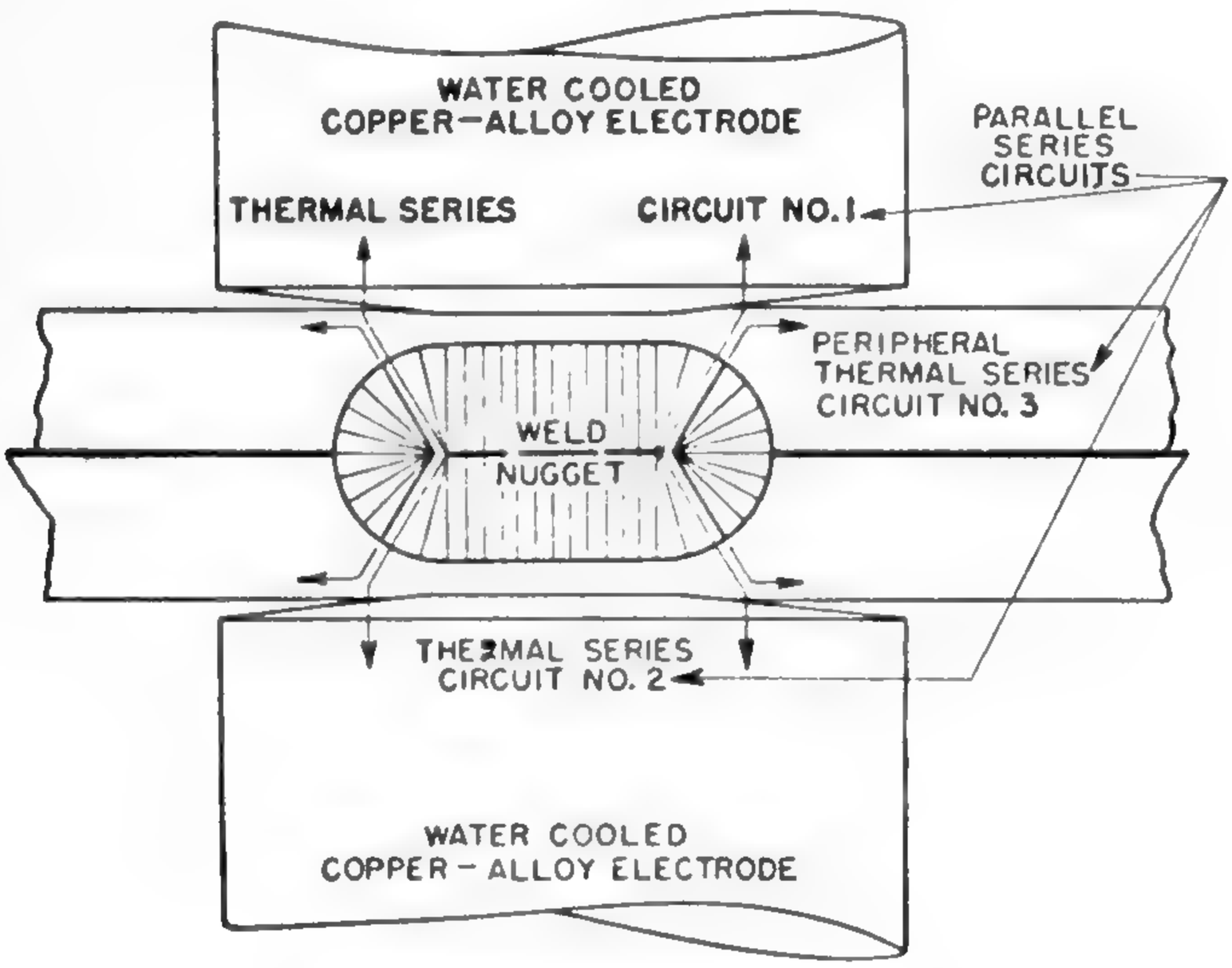


Fig. 10.—Heat Flow in Spot Weld

perature differential between it and the weld nugget, which is important in governing cooling rates. For heavy masses of metal, where longer spot welding times are generally employed, the cooling rates will be slower, whereas in very thin sheets or in projections on heavy stock where shorter times are employed, the quench rate is drastic.

If the electrodes are removed from the weld immediately, the heat is dissipated into the atmosphere and the metal surrounding the weld zone and the quench rate is somewhat reduced. In the case of thin sheets this procedure may be objectionable on account of warpage while for heavy stock adequate time to permit cooling of the larger mass below the molten state is necessary for strength reasons. Therefore, it is usually desirable to leave the electrodes in place for a sufficient time to permit cooling of the weld without allowing complete transfer of the heat into the surrounding volume of metal. Production demands in many cases necessitate a compromise, cutting the hold time to a minimum.

In the case of seam welds, the hold time becomes short, because of the continuous rotation of the electrodes. Therefore, it is necessary to flood cool the work to remove the heat as rapidly as possible. In some cases, it is desirable to make the weld completely submerged in water.

It is not always desirable to rapidly cool the weld. In the case of quench-sensitive metals, it is usually desirable to remove the electrodes as quickly as possible to permit the heat to radiate into the surrounding metal, which tends to smooth out an otherwise steep quench gradient.

Forging Pressure.—The clamping force used to best achieve the required heat quantity may not be adequate to consolidate the weld nugget so that it will be free of internal porosity or cracking, depending upon the metal composition, weld size and work thickness. In these instances multilevel force machines may be employed to provide additional pressures during weld solidification.

The magnitude of these pressures will vary with the composition and thickness of the metal and of the geometry of the parts, but the forging or cooling pressure is commonly two or three times that used during welding.

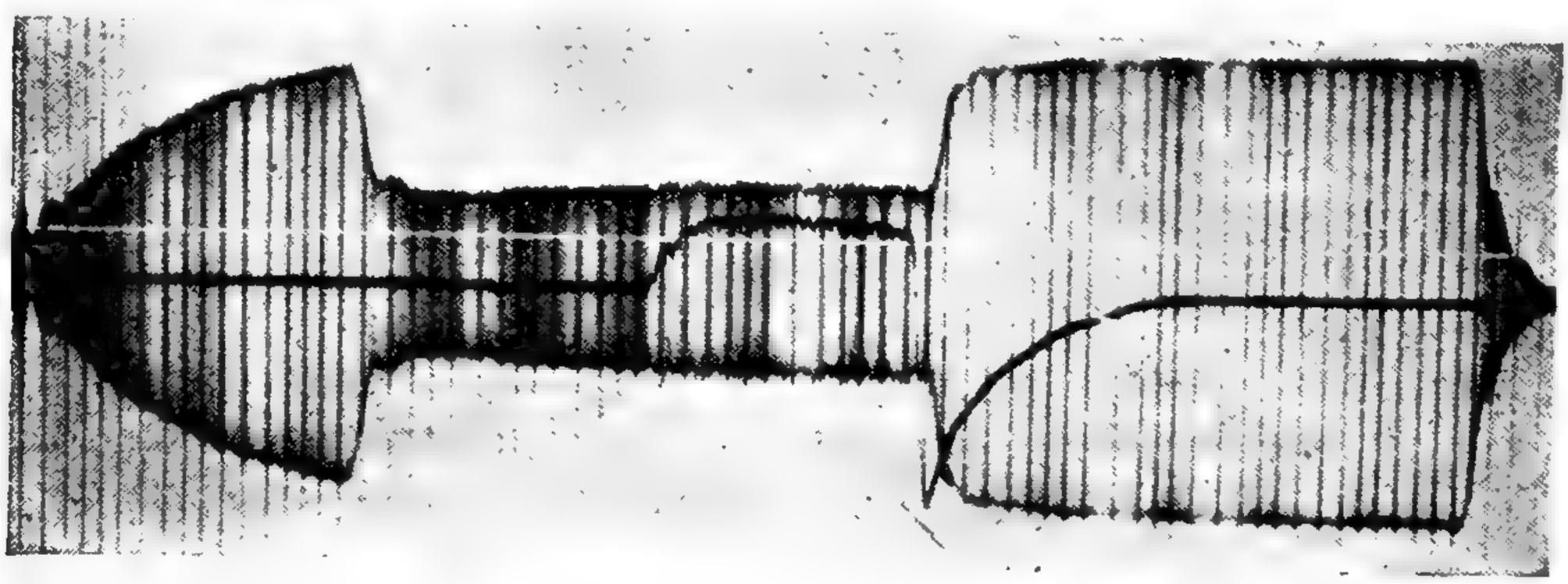


Fig. 11.—Oscillogram Showing Relationship Between Current and Pressure in Electro-Magnetic Stored Energy Machine

Note: Vertical lines denote electrode force; horizontal lines current.

Since the weld cools from the periphery inward (Fig. 10), it is necessary that the forging pressure be applied at or close to the current termination point in a.c. welding and at or after the peak of the surge with the d.c. surge type of current application. An illustration of the relations of forging pressure application and current termination are shown in Fig. 11.

Surface Preparation.—The purpose of preweld surface preparation is to control the magnitude and to minimize variations of the contact resistance at the faying surfaces of the work parts and the contact resistance between the external work surfaces and the welding electrodes.

Surface resistance is caused by the presence on the work parts of foreign substances either deposited in the course of handling or formed chemically by

the action of atmosphere or other agents brought in contact with the work during its fabrication. The mechanical and chemical films constituting the surface resistance of metals are in no way similar and different methods must be employed for their removal.

The fundamental principle of spot, seam and projection welding is the creation of fusion between the contacting surfaces of the parts joined and not on their outside surfaces. Heat produced between electrode surfaces and the work parts welded is usually harmful, particularly so if surface marking of the work is to be avoided.

Dirt and oxide film from the surfaces of the parts welded which may come in contact with the electrodes must be removed or reduced in resistance to insure welds with good surface appearance and to minimize electrode pickup and thus increase electrode life. The need of likewise treating the resistance film on the faying surfaces of the material is equally great. Any deposited film such as oil, dirt, etc., will not be uniform. This introduces variations into the contact resistance which in turn vary the amount of welding heat generated.

Methods of Cleaning.—There are a number of means of removing the mechanically deposited film of dirt or oil from the surfaces of work parts to be welded. Vapor degreasers and chemical baths are the most satisfactory, although with proper supervision and technique hand wiping can be satisfactory.

The removal of foreign substances such as oil or dirt from the work parts is not only necessary for its own sake but also in order to permit the subsequent removal of the oxide film since most of the means capable of attacking this film are rendered, to a large degree, ineffective by the presence of oil or grease, and will not operate unless the surface is chemically clean, that is, will support a water film.

The chemically formed film of oxide present on all surfaces can be scraped off by mechanical operations. The action must be sufficiently severe to cut through the oxide film yet gentle enough to prevent formation of an excessively rough or scratched surface. In the case of clad or coated materials, the action must be controlled to guard against appreciable removal of the cladding. For this reason the bristles of wire brushes and the grades of abrasive used must be sufficiently fine to produce comparatively slow removal of material with each application.

The principal advantages of mechanical methods of surface cleaning are:

1. Ability to remove surface films locally without danger of subsequent deposit of other high resistance films.
2. Ability to remove surface films from any part of a surface without the need of treating the entire surface.
3. Low capital investment.

The principal disadvantages of the mechanical methods of surface cleaning are:

1. High labor cost since steel wool, wire brush or abrasive, depending upon the metal, must often be applied to the surface by hand and the removal is comparatively slow.
2. Difficulty of insuring uniform action since the extent of removal depends on the force applied by the operator to the rotary brush or abrasive sander or steel wool pad and the length of application of these means to any one spot.

If, due to economy or other factors, it is not practical to use pickled stock, either purchased as such or pickled in the fabricator's plant, the only recourse is to grind or polish the edges to be welded. This polishing must extend sufficiently back from the edge of the work part to fully clear the width of the electrodes. It can be done by hand or by machine. Some fabricators have found it more economical to devise semi-automatic machines for grinding the edges than to use pickled stock. This method also has the advantage that except for the weld line the protective coating of scale is left intact. This feature is desirable for automobile mufflers, etc.

Other methods of cleaning such as sand, coarse grit or shot blasting are not satisfactory since they tend to embed particles of sand or scale into the surface. However, the use of fine sharp steel grit-blasting has been found to be satisfactory.

Annealing in a reducing atmosphere is also a satisfactory cleaning method for some materials.

The principal advantages of the chemical methods of cleaning are:

1. Uniformity of results and ability to reproduce consistently the same surface condition, provided proper process control is exercised.

2. Low unit labor cost, since with proper installation the only labor cost is in loading and unloading of the cleaning basket.

The principal disadvantages of the chemical method of cleaning are:

1. Necessity with some metals to control accurately the time of exposure of the surface treated to the action of the agent used, since either over- or under-exposure may result in higher surface resistance for these alloys.
2. Presence of corrosive acids or alkalies on the factory floor and their potential danger to personnel.
3. Comparatively elaborate installation including corrosion-resisting tanks, automatic temperature and time controls, hoists, dipping baskets, etc.

The chemical methods are widely used; specific cleaning agents vary with material composition.

Metals manufacturers can usually provide thorough information on cleaning methods.

Surface Preparation Control.—Surface preparation control is checked by measuring the cold contact resistance of the surfaces involved. This is most readily measured from electrode tip-to-tip through two or more pieces of stock, but the measurement can be made for any contacting areas. Unit surface resistance varies inversely with pressure, temperature and area of contact. These values must be known and specified in order that reported values have significance.

SPOT WELDING

Spot Welding Methods

Regardless of the type and source of current employed to generate the welding heat as described under the preceding fundamentals and of the specific mechanical characteristics of the machines, spot welding production methods may be divided into two classes: the making of single welds and the making of multiple welds. A single spot weld is a weld made by current flowing through only one weld spot during any specific period of current flow. Figure 12 illustrates examples of single welds. Figure 12*C* is considered a single weld even though multiple points are used, because current-time sequencing insures against simultaneous current flow through more than one weld during any one period. Multiple welding consists of making two or more spots simultaneously during one specific period of current flow.

Single Welding.—Single welds may be made either directly or indirectly as to current path. Figures 12 *D* to *F* show examples of indirect welds made with a single transformer wherein only one weld is made because of the differences in contacting area of the two electrodes shown. Figures 12 *G* and *H* show single indirect welds made with multitransformers.

Multiple Welding.—Multiple welds may also be made by direct or indirect means, as illustrated in Fig. 13. Examples *L* and *M* are series welds. While applications of single and multiple-spot welds follow the general theory of Figs. 12 and 13 the individual specific arrangements may vary.

Series Welding.—Welds made by the methods shown in Fig. 13, *L*, *M* and *N*, are series welds and depend for their successful application upon an accurate knowledge of the relative resistance of the several parallel paths available to current flow. For example, in Fig. 13*L* the dimension between contact points and the thickness of the material contacted by the electrodes must be such that a majority of the current will pass from the electrode down through the spot to be welded, through the copper shorting block and back up through the contacting electrode rather than flow through the upper plate between the contact points. A specific example may be cited where it was required to weld three thicknesses of $^{3}/_{32}$-in. thick low-carbon steel in the manner illustrated. Experiment determined it to be necessary to space welds on 6-in. centers to avoid excessive shunting of welding current through the top members. If closer spot spacing was desired, it would be necessary to backstep, still keeping the electrodes on 6-in. centers. The illustrations have shown regular spot welding electrodes, but circular electrodes may be also used as electrodes for roll-spot welding with the possible exception in Fig. 13 *N*. In this case, the resistance of the wheel bearings would probably be too high for most applications.

Parallel Welding.—In parallel welding, the current is passed through several pairs of electrodes and divided into parallel paths. The individual path distribution

of the current is determined by the relative resistances of each path in accordance with the laws of electric current flow, the most current going through the path of the lowest resistance. Since it is difficult to maintain equal resistances in each path, uniform distribution of current is not always obtained and the results are accordingly not always uniform.

it is impractical to attempt to prespecify welding schedules for every conceivable condition and combination. However, for the most commonly welded metals, data have been compiled by the AWS Resistance Welding Committee to serve as a guide for the welding of those metals. These *Recommended Practices* are shown in Tables 1 to 7, inclusive. (Data on pul-

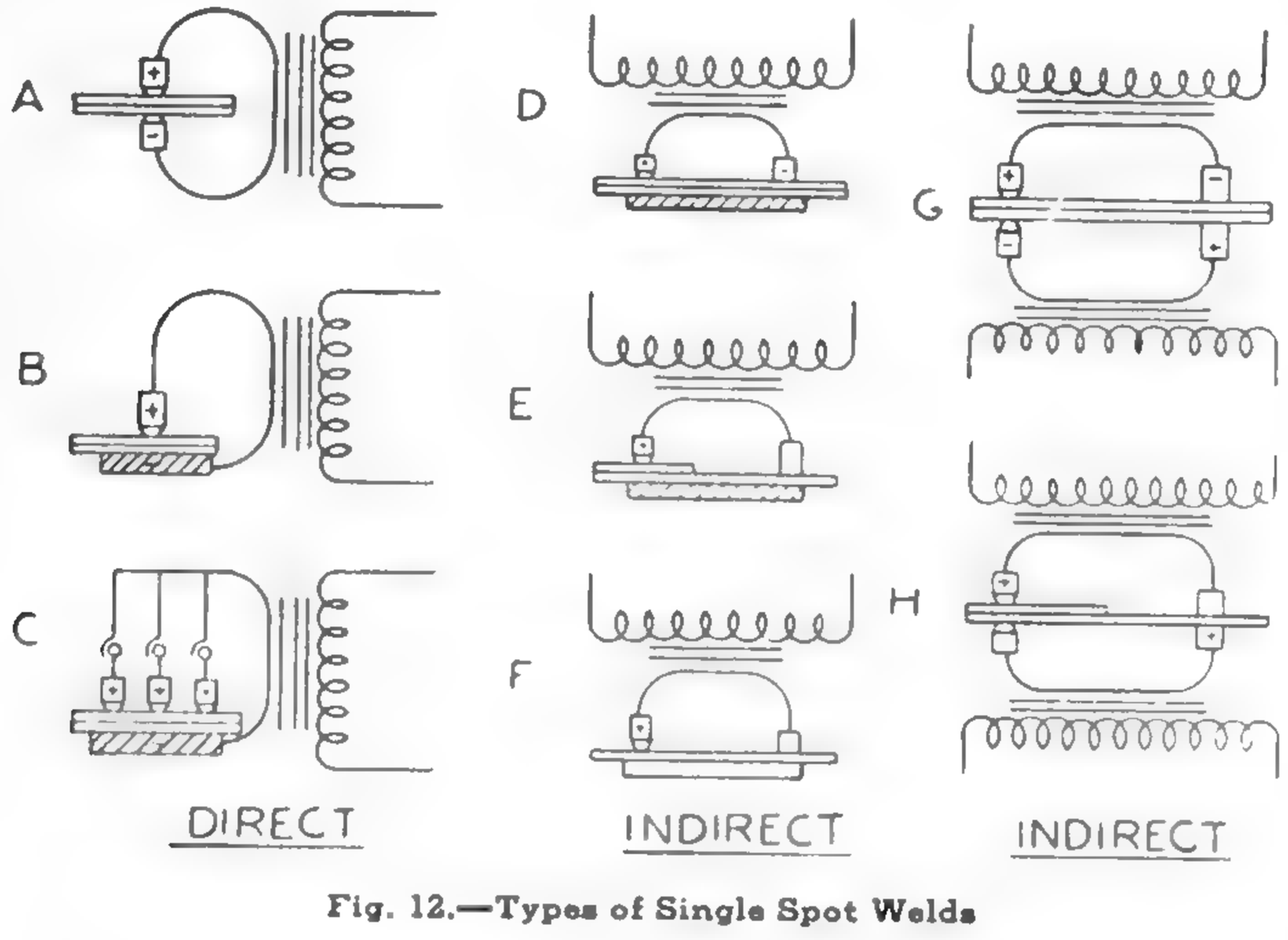


Fig. 12.—Types of Single Spot Welds

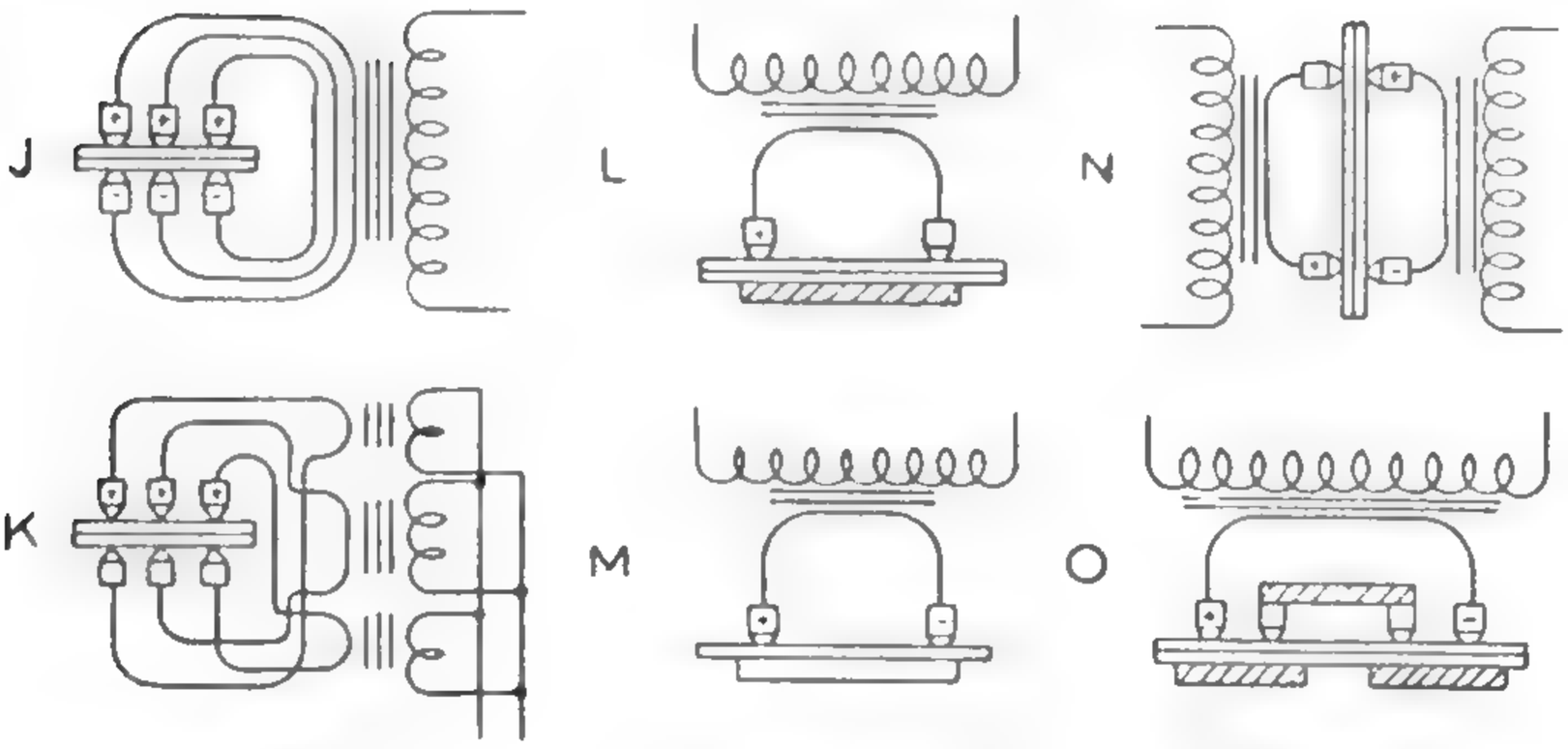


Fig. 13.—Types of Multiple Spot Welds

Spot Welding Schedules

From the dimensions, properties and characteristics of the metals to be welded, the specific type of welding equipment and methods to be employed, and the joint design involved, it is possible to establish a welding schedule for any particular combination of these variables. With the obvious multiplicity of variables involved

sation welding will be found in Tables 14 and 15.)

The schedules have been compiled to provide uniform information for use by the design, manufacturing and inspection departments. In order to obtain uniform production it is necessary that these three groups employ the same welding data because of the interrelated requirements of design, welding practice, and results

produced. The designer must be guided in choice of overlap, flange width, weld spacings and weld strengths by the equipment and conditions to be employed in the manufacture of the product. To assure that the anticipated weld strengths are achieved, the manufacturing units should employ the applicable factors of the schedule—eletrode dimensions, force, current and time—as specified.

Welding Current: The values given in the *Recommended Practices* are approximate and are intended to help calculate and specify the capacity of welding machines. They should not be used as exact values to obtain a given weld strength. The current may be increased to the point where metal expulsion occurs and then reduced to just below this point; optimum strengths may thus be obtained.

Time: The values shown for all time factors are in cycles based on 60 per sec., except that the *Weld Time* for pulsation welding is in number of current pulsations.

Force: The values refer to the net forces between contact surfaces, such as would be obtained in actual welding.

Electrodes: Two forms of electrode are shown, one having a flat face and beveled sides, the other having a dome-type face. The domed-type is easier to maintain in service and its use is preferred.

Where the flat-face electrode is used, the small diameter, *d*, should not exceed the value specified in order to control electrode contact area. On the other hand, use of a much smaller end diameter than specified will cause metal expulsion and a reduction in weld strength. In use, care should be exercised to prevent excessive increase in the contacting diameter by dressing to size when required.

The electrode body diameter, *D*, is a minimum; use of smaller diameter than specified will result in over heating and excessive mushrooming.

Heat Balance

Heat balance may be defined as a condition in which the fusion zones of both pieces of material to be joined undergo approximately the same degree of heating and pressure application. Heat balance is influenced by:

1. Relative thermal and electrical conductivities of the materials to be joined.
2. Relative geometry of the parts to be joined.
3. Thermal and electrical conductivities of the electrodes.
4. Geometry of the electrodes.

It is desired, for example, to weld a high copper content alloy of high thermal and electrical conductivity to a material of low thermal and electrical conductivity such as stainless steel. In this case the weld may not be of the best quality due to a poor alloying condition of the dissimilar materials, but the nearest approach to a satisfactory weld would be accomplished by using one of the techniques shown in Fig. 14.

Figure 14*A* shows a correct heat balance obtained by using a smaller electrode area on the copper alloy than on the steel alloy to obtain approximately equal degrees of fusion by variable current density. Figure 14*B* shows a correct heat balance obtained by using an electrode with a facing of high thermal resistance material such as tungsten or molybdenum to create approximately the same fusion in the copper alloy as in the steel alloy. Figure 14*C* indicates the use of a combination of both techniques shown by Figs. 14*A* and *B*.

A proper heat balance may also be achieved in these two dissimilar alloys by the method indicated in Fig. 14*D* where the increase in the thickness of the higher conductivity alloy compensates for the higher conductivity.

An artificial method of creating a heat balance sometimes employed consists in the

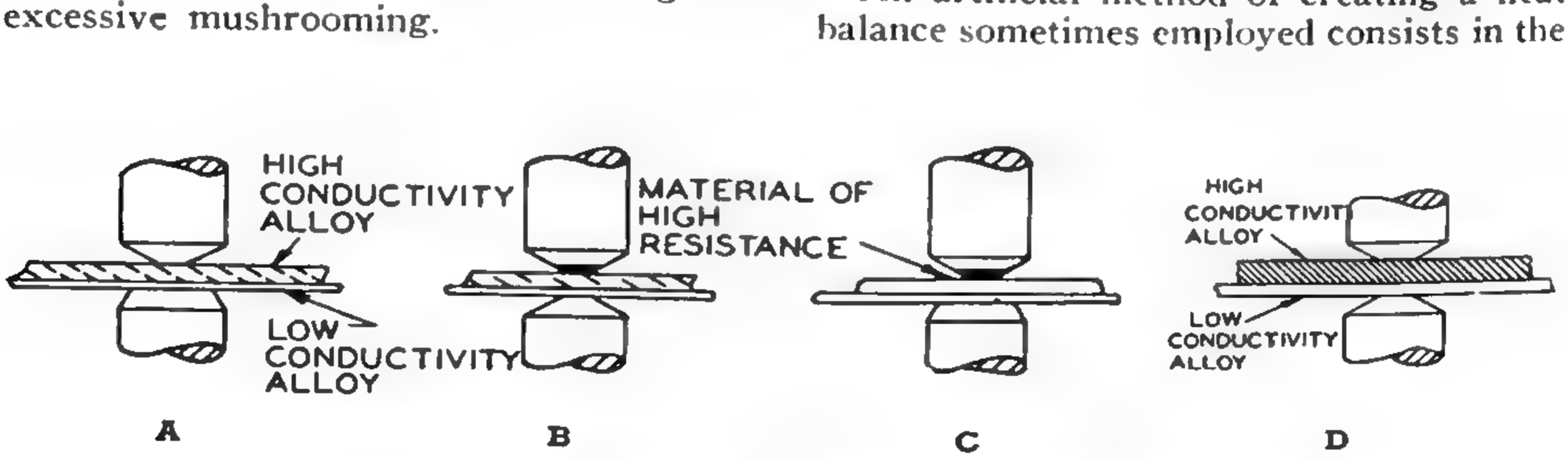


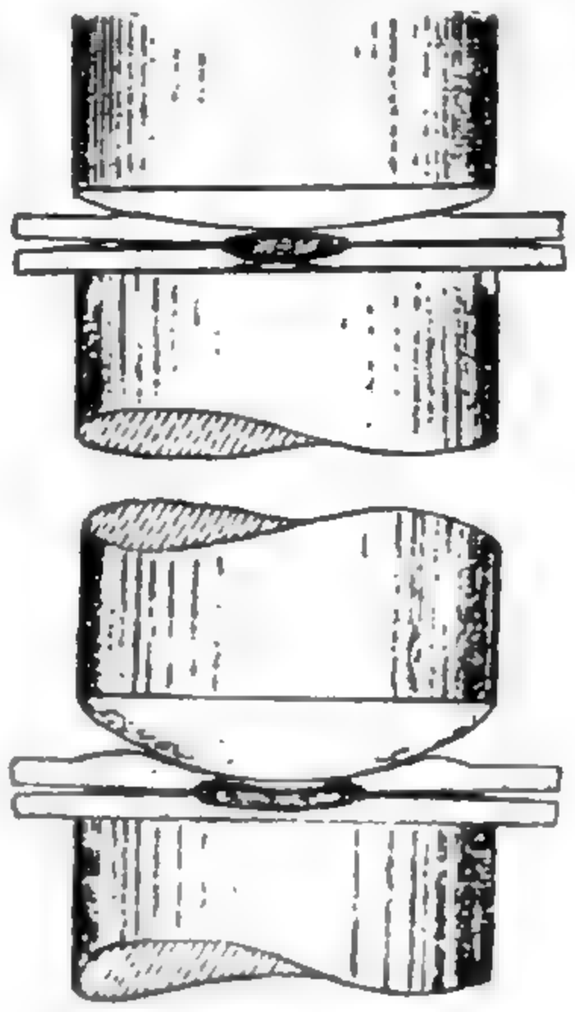
Fig. 14.—Techniques for Obtaining Heat Balance in Spot Welding Dissimilar Metals

use of a thin plating of lower conductivity material or the insertion of thin strips of such material between the two pieces of work to be welded. Tin plating of copper or brass is an example of this technique. The plating is very thin, being measured in ten thousandths of an inch.

Heat Shrinkage

It is often desirable to produce flush or invisible welds. This may be closely approximated if all factors are closely controlled. In order to attain the best results, it is necessary to understand the most important factor, which is heat shrinkage. When the work is heated, (Fig. 6) it tends to expand in all directions, but due to the pressure exerted by the electrodes, any vertical expansion is immediately forged out, with the result that all of the local expansion takes place in the horizontal plane, usually causing a slight ridge as shown at *A*, Fig. 15. In cooling, the contraction takes place along the lines of least resistance, or almost entirely in the vertical plane, which results in the concave surfaces shown. This is not to be confused with electrode marks (Fig. 16) where the electrodes embed themselves into the work due to improper control. Little actual depth of shrinkage depression exists, usually not over a few thousandths of an inch, but in some forms of finishing operations and with certain forms of light reflection it is conspicuously noticeable. It is almost impossible to completely eliminate these heat shrinkage marks, but they may be materially reduced by proper control, that is, by making the welds in a short time, thereby preventing as much as possible the radiation of heat to the surface.

Various techniques are used to minimize



g. 16.—Causes of Electrode Markings on Material Surface

these markings. The most common method is to use an electrode of greater area on the side of the material which is desired to have a minimum of marking as in Fig. 14*A*. If this electrode is made of a copper alloy having a higher proportional limit than that of hard-rolled copper, the surface contacting the weld does not deform due to heat and pressure as quickly and thus minimizes surface marking of the welded material.

One method, shown in Fig. 17, recognizes that the marking cannot be prevented entirely and that an imperfection can more readily be dressed off if it is above rather than below the material surface. Such a condition is deliberately created by using a depression in the electrode contacting the surface to be finished. The hot metal conforms to this depression and, being above the surface of the surrounding material, is more easily removed. However, when using this method, a depression around the periphery of the weld may be obtained.

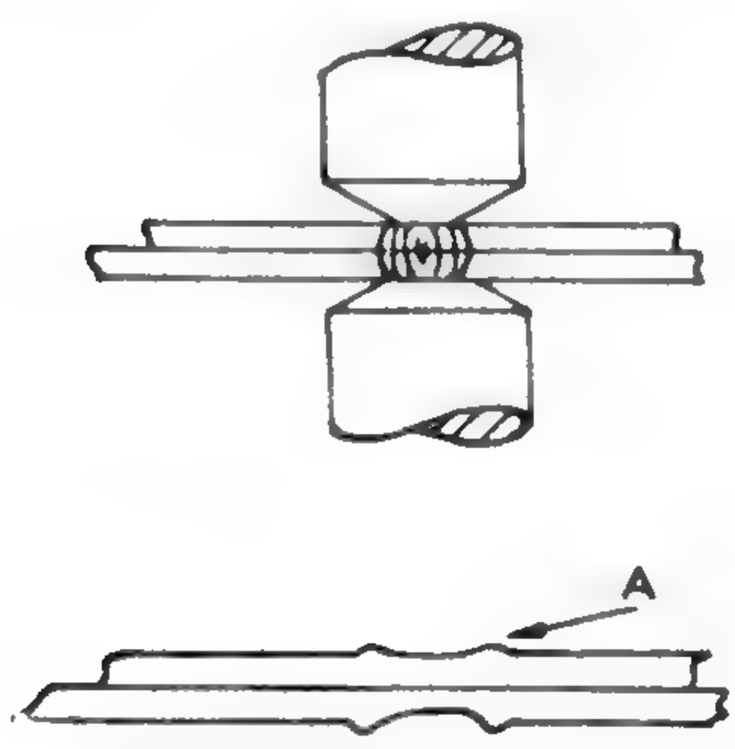


Fig. 15.—Effect of Heat Shrinkage on Spot Welds

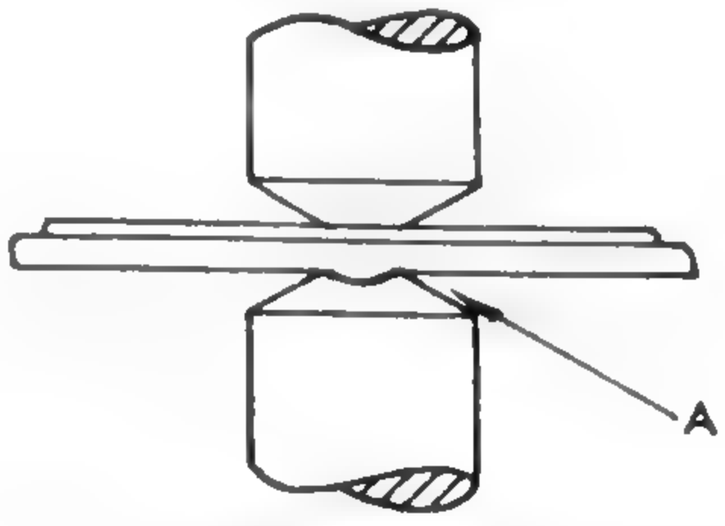


Fig. 17.—Depression in Electrode Used to Prevent Surface Indentation

Indirect introduction of current to the weld as shown in Fig. 18 assists in obtaining a minimum of marking on Part *B* by affecting current distribution in that part.

ROLL-SPOT WELDING

Roll-Spot Welding Methods

Roll-spot welding consists of making a series of separately spaced spot welds in a row by means of one or two rotating circular electrodes without retracting the electrodes or removing the welding force between spots. The same principles apply as have been explained for spot welding. The radius of the electrode determines the contacting longitudinal radius of the electrode. The use of the same transverse radius in effect provides a domed or spherical electrode.

The weld spacing is obtained by proper adjustment of electrode speed and current off time, using conventional seam-welding machines. The individual roll-spot welds are essentially the same as spot welds made in the usual manner except that shorter hold times are employed and, due to electrode travel, the welds tend to have an elongated nugget. Single and multiple welds may be made as discussed under spot welding.

ployed, which may sometimes require the use of higher roll forces.

SEAM WELDING

Seam Welding Methods

Continuous Motion.—The electrodes are driven at a constant speed consistent with the particular work being done or, in some cases, the work is pushed or pulled at a constant speed and the electrodes idle under the proper electrode force.

The electrode drive on seam-welding machines may take several forms. In the standard seam-welding machine, the upper or lower wheel may be directly gear driven by a motor through a gear box and clutch. Also both electrodes may be driven with a knurl drive, which is a steel disc or roll formed to fit the face of the electrode a short distance up its side with the surface contacting the face of the electrode being knurled to give traction. The knurled type of drive propels both wheels at the same peripheral speed, irrespective of their diameter and is particularly adaptable to the welding of coated materials such as tin plate, terne plate and galvanized iron, as this type of drive tends to break up the coating from these materials picked up on the

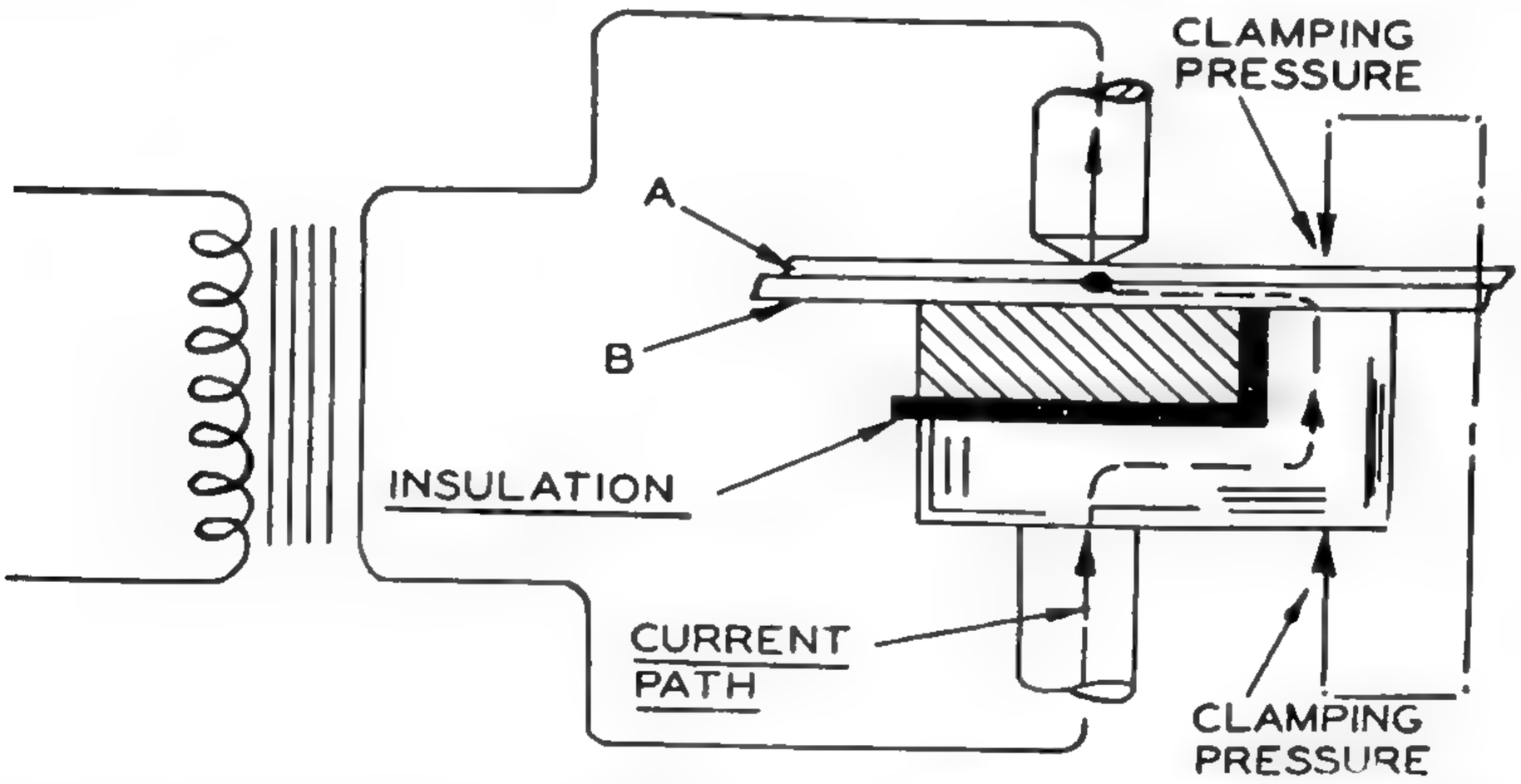


Fig. 18.—Indirect Introduction of Current to Minimize Surface Markings

Roll-Spot Welding Schedules

When continuously moving electrodes are employed, as is commonly the case, welding times are usually held to lesser values than for spot welding and therefore somewhat higher currents are employed, which may sometimes require the use of higher roll forces.

face of the electrodes. In the traveling roll-type machine, the work is clamped to a bar electrode and pushed under an idler electrode, power being applied to push the work rather than to rotate the electrode. In other cases the electrode

mounting member is pushed parallel to the seam resting on the bar electrode. In multiple seam-welding equipment, where two wheels are connected in series across the transformer and the bar electrodes are used as shunting members under the work, a hydraulic drive is usually used as it gives a smoother and more constant-speed motion than most types of mechanical drive.

In making several parallel seams on flat work, electrodes in multiples of two—each pair with its own transformer—may be used, as there are no current interferences between the various pairs of electrodes on the same work-piece in this method of series welding.

Intermittent Motion.—Where the work parts are too thick to be satisfactorily welded by the continuous motion method, usually $^{3}/_{16}$ in. or greater, an intermittent drive may be applied to the work or electrodes by the Geneva motion of gearing or by a stop-and-start electrical control on the driving motor. In this way the work progresses between the electrodes the distance required for each succeeding weld increment and stops during the time required to properly make each individual weld, then automatically moves the proper distance for the next weld increment; this is repeated for the full length of the weld.

In intermittent motion welding an interrupter may be used with continuous interruptions or a spot weld timer may be used, arranged to give a measured time of current application each time the intermittent motion ceases.

Interrupted current is usually necessary for most seam welding as it gives much better control of the heat, allows each successive increment in the seam to cool under pressure, gives less distortion to work parts due to overheating of material adjacent to the weld, gives better control of flashes or burns caused by adverse conditions of material and makes sound welds with less surface disturbance. The choice of the correct type of interrupter is important. The synchronous electronic interrupter is the best type for seam welding (see Chapter 15). The use of mechanical interrupters for seam welding is not advised due to their non-synchronous switching, slow speed and other inherent inaccuracies. A type of seam welding where an interrupter is not necessary is that which welds at high enough speeds so that the frequency of the electrical circuit itself acts as an interrupter. Also no interrupter is required for some conditions of welding with direct current.

Types of Welds

There are several different types of seam welds, and these are generally similar to spot welding applications. The most commonly used type is the simple lap seam weld, Fig. 19, in which the pieces or edges to be welded are lapped sufficiently to prevent spitting of the weld metal from the edges of the stock. Common examples are the lap joints in cans, buckets, water tanks, mufflers, large diameter thin wall pipes, etc.

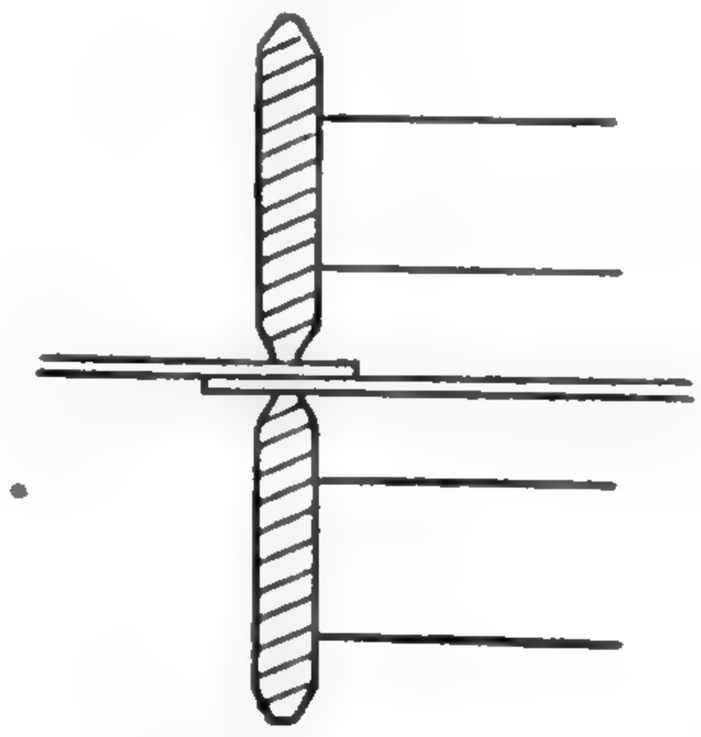


Fig. 19.—Common Type of Lap Seam Weld

Similar to this is the flange joint, shown in Fig. 20. At *A*, one of the pieces is straight. This is a construction commonly used for welding out-turned flanged bottoms or tops to containers of various types. At *B*, both pieces are shown flanged. This design is used on automotive gasoline tanks, etc. Often the flanged pieces are dished to obtain added strength. In this case it is necessary to mount one or both wheels at an angle to clear the work. Best practice limits this angle to 6 deg. although angles up to 10 deg. have been used. Angles greater than 6 deg. complicate the machine design by causing excessive bearing thrust, lack of bearing clearance and the necessity for using larger welding electrodes.

It is sometimes necessary to place the electrodes at an angle for the *A* and *B* types also, especially if the radius at the flanges is too small to permit sufficient clearance between the electrode and the work. On small diameter containers with

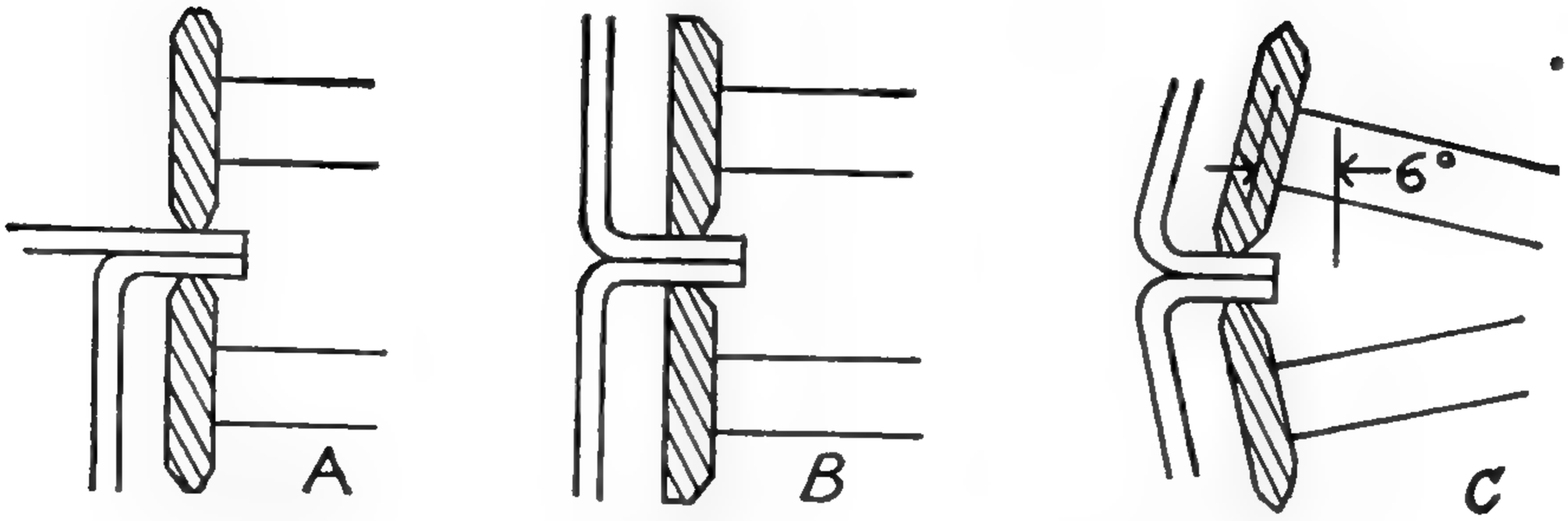


Fig. 20.—Common Types of Seam-Welded Flanged Joints

dished heads it is often impossible to place the wheel at an angle to clear the dish. Figure 21 shows an alternative construction which uses one special electrode. This is to be avoided where possible due to greater cost and shorter electrode life.

The joint types in Fig. 20 may be used in either flat or round parts. Designs of the type shown in Fig. 22 involve rectangular containers. One application consists of welding 2-in. radius corners into a rectangular container measuring about 14 in. per side. Obviously the lower welding wheel must have a radius less than that of the corner, for example, $1^{7}/_{8}$ in. ($3^{3}/_{4}$-in. diameter). Due to the differences in area of contact of both the upper and lower electrodes, entirely different welding conditions are presented in welding the corners as compared with welding the straight sides. In practice, since welding the corners is slower and more difficult, the machine is set for this condition, at a sacrifice in welding speed for the balance of the seam.

Another type of seam weld commonly used is the mash seam weld. This is a weld in which the overlap is considerably less than for the lap joint. Sheet $^{1}/_{16}$-in. thick is about the heaviest stock that can be successfully mash seam welded. If the overlap is held at about $1^{1}/_{2}$ times the stock thickness and the machine is operated at a reduced speed, with higher pressure and non-interrupted current, the resultant weld will be strong, of high quality and with a *bump* or weld thickness not more than 10 to 25% greater than the thickness of the sheet. Flat electrodes are used, sufficiently wide to completely cover the overlap. This type of weld is used extensively for refrigerator cabinets, stoves and many porcelain enameled applications. The amount of excess thickness at the weld, the amount of overlap and the speed of operation are all interrelated and can be regulated to meet specific requirements of the finished product. Preweld tacking or otherwise rigidly clamping the work parts to maintain the exact overlap ahead of the welding electrodes is important.

Low-carbon steel is considered to be the most satisfactory metal for mash seam welding, but stainless steel has been mash seam welded for certain applications. Nonferrous metals cannot be mash welded because of their narrow plastic range. For best results wheel electrodes must be used on each side of the weld. A mandrel can be used in place of one of the electrodes, but the mash will not be as complete. If the overlap of a mash seam weld is reduced to zero, that is, the edges butted together, and the same procedure used, there will result, instead of a ridge, a slight depression in which both ends of the abutting pieces are heated, mashed and to a slight extent forged together. The resulting weld may be of sufficient strength for some applications. A third type of seam weld is the butt-seam weld, which is commonly used in the manufacture of electric welded piping and tubing. A variation of this, but still constituting a seam weld, is sometimes resorted to for such applications as toys, automobile horns and other inexpensive and low strength joints.

Direct Welds.—The electrodes contact the work-piece directly opposite each other and consist of two circular electrodes or one circular electrode and a bar, as illustrated in Fig. 12, *A* and *B*.

Indirect Welds.—One electrode contacts the work directly and the other electrode which may be circular, a bar or a shoe contacts either the work on the same side, but in a remote area, or contacts a fixture or bar arranged to complete the re-

turn circuit, as illustrated in Fig. 12, *D*, *E* and *F*.

Series Welds.—In series seam welding both rotating electrodes are on the same side of the work part and a short-circuiting bar placed on the other side for the return circuit (Fig. 13*L*), or in addition to the bar, circular electrodes electrically connected by a shaft may be used. With this arrangement, two seam welds are made simultaneously.

Multitransformer Seam Welds.—An arrangement of two or more pairs of circular electrodes or circular and bar electrodes, each pair with its separate transformer as illustrated in Fig. 13*K*, making two or more seam welds simultaneously. This is a multiple arrangement of direct welding.

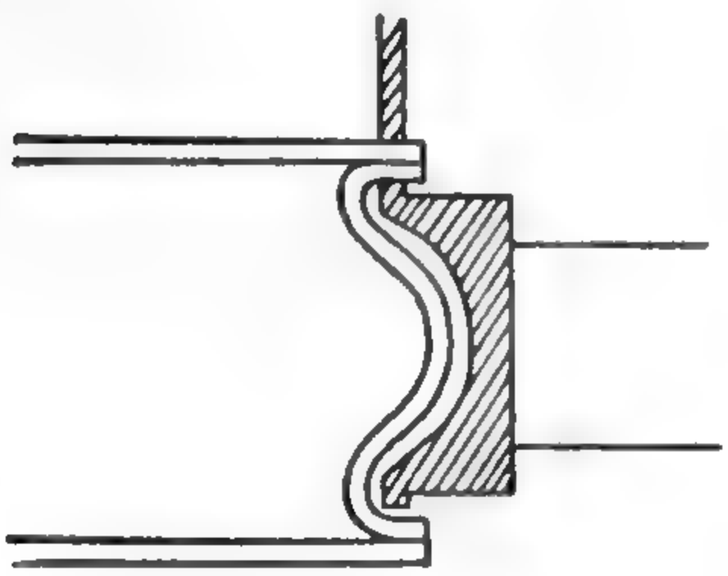


Fig. 21.—Special Electrode for Seam Welding Dished Heads

Single Row Welds.—Seam welds made where the two edges of the material are lapped sufficiently so that cool material will be left on each side of the weld, of sufficient width to support the hot metal and prevent the expulsion of the metal forming the weld nugget, Fig. 19.

Multiple Row Welds.—Seam welds made parallel to each other, usually with two or more pieces of metal lapped their full width, made in several passes with one set of electrodes or made in one pass with parallel electrodes.

Continuous Welds.—A seam weld made where each individual spot overlaps the preceding one, making a gas or liquid pressure tight weld.

Intermittent Seam Welds.—A seam weld where each individual weld contains a number of overlapping spot welds or weld increments making a joint which has good mechanical strength but is not pressure tight.

Welding Schedules

Current and Voltage.—The correct welding current is so dependent upon other conditions that it is not practical to give rules for its determination. For example, the amount of cooling water applied to the electrodes will change the current requirements. General statements might be made such as: the shorter the time *on* or the faster the welding speed the more the current required but, first, all the other variables should be established and then the current determined by trial and error until the desired quality of weld is obtained. Recommended Practices for the most commonly welded metals are given in Tables 8 and 9.

Required transformer tap voltage is dependent on type and thickness of material, speed of welding, throat depth, and surface condition of material as well as the welding machine impedance but is usually somewhat higher than used for spot welding the same thickness of material because higher currents are required due to the continuous shunting effects and the distribution of the current and weld areas.

Time.—It cannot be said that any definite timing schedule is the best for a given stock. There are many other variables which influence the choice such as welding speed, capacity of the machine, thickness of stock, type of joint desired, etc

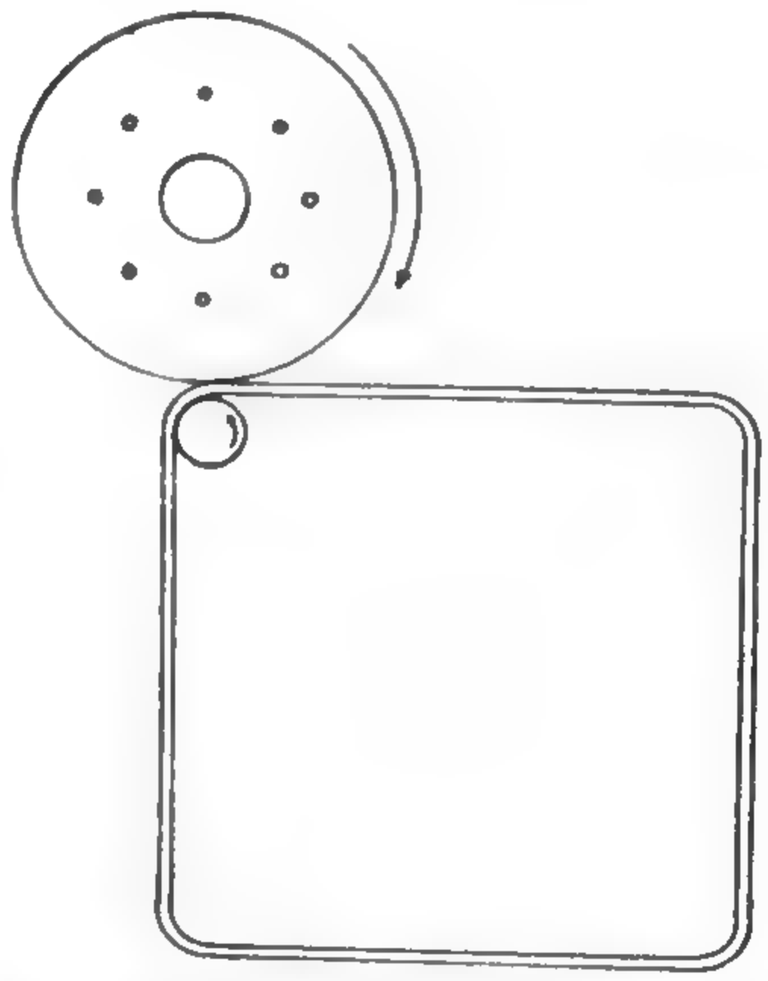


Fig. 22.—Use of Small Diameter Electrode for Seam Welding Corner Joints

Assuming a gas or liquid-tight joint is desired, the best timing will be that which will allow the fastest welding speed within the capacity of the machine. For practical purposes and best results the time *on* should be equal to or greater than the time *off*. The time on is determined largely by the thickness of stock while the time off is determined by the welding speed. That is, the thicker the stock the longer the time on while the faster the welding speed the shorter the time off.

Force.—The electrode forces used for seam welding are usually higher than those used for spot welding the same material. The fit of the material in the joint has much to do with the force required. The material should fit closely together and be free from wrinkles and excess material in one piece over the other. Slack between the two pieces will run ahead of the wheel electrodes and give trouble near the end of the weld. This is of particular significance for circular parts like the bottom in a tank or can.

Bar electrodes may assume the face shape as shown in *A* or *B*.

The diameters may vary from a minimum of 2 in. to as much as 2 ft. for special machines. However, the common range is from about 6 to 10 inches. The usual material is a copper alloy of the heat-treated, precipitation-hardening type.

The edge or face, in contact with the work usually has a slight crown and rounded corners.

The rate of electrode wear is determined by the pressure used; the surface condition and analysis of the material being welded; the electrode temperature as influenced by values of welding current and amounts of cooling water; abrasion of work and drive rolls; and the material used for the electrode.

As heavier thicknesses of materials are welded using heavier forces and higher currents, the face widths of the electrodes must be increased to avoid excessive pressure and current density in the work.

The width of the weld at a point on the center line between the two work-pieces ranges from $1^1/_2$ to 3 times the thickness of the thinner piece being welded. The higher ratio of weld width to plate thickness occurs when welding the thinner thicknesses and this ratio decreases as the material increases in thickness. The lower limit of commercially practical electrode face width is approximately $^1/_8$ to $^3/_{16}$ in. because of excessive electrode wear. This explains the high ratio of weld width to sheet thickness for the lesser work thicknesses. The weld width is always slightly less than the face width when commercially practical welding

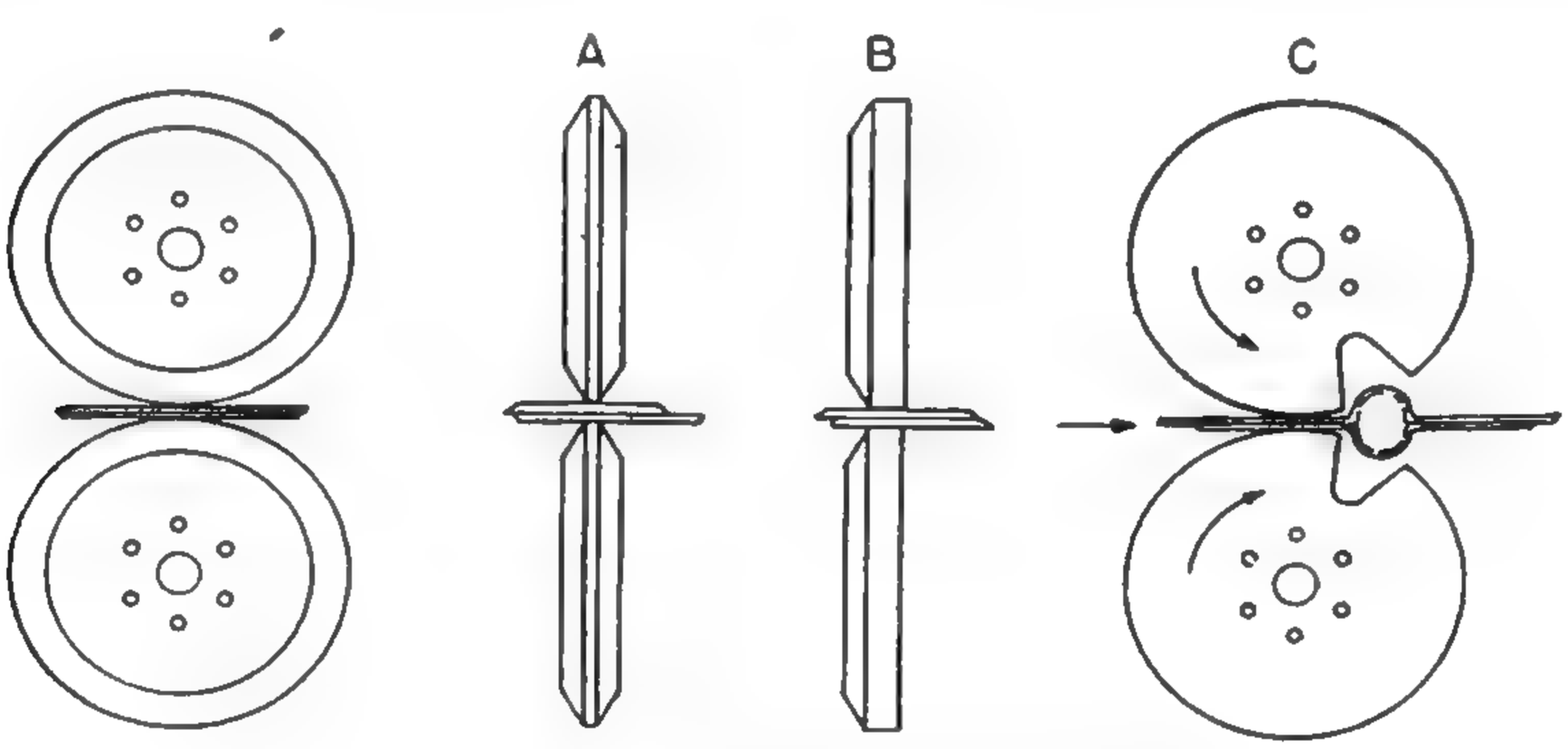


Fig. 23.—Shapes of Seam-Welding Electrodes

Electrodes.—Electrode shapes are shown in Fig. 23—*A* being the electrode used where clearance is available on both sides of the work, *B* where the weld must be made close to an obstruction such as a flange or the bottom of a tank-type structure, *C* where an obstruction may be at right angles to a seam. A notched electrode can be used for bridging transverse obstructions each time with a notch close to the obstruction and rolling away from the obstruction with the electrode. Where the obstruction is on one side only, a notched electrode as shown in *C* and a plain electrode as shown in *A* may be used.

schedules are used. An estimate of weld widths being 80% of electrode width is approximately correct.

External Cooling

In seam welding, either flood or immersion cooling is used. This is in addition to the internal cooling of the arms and secondary circuit of the welding transformer. Where no flood cooling is used on the work or the welding electrodes, excessive electrode maintenance and badly warped work are usually the result. In welding nonferrous materials and stainless steel, ordinary clean tap water is satisfactory. When welding the ordinary steels which are susceptible to rusting after becoming wet, a 5% borax solution is commonly used. This solution may be recirculated by a small motor and pump at each machine coupled with a small subtank of sufficient capacity to take care of the particular welding machine. Where a number of welding machines are located in close proximity to each other, it is usually economical to install a large tank and have the solution drained or pumped into this tank and have a common tank for the complete installation. Whether the single machine tank or the large tank is used, adequate water cooling coils should be inserted in the tank to keep the borax solution cool enough for satisfactory cooling of the electrodes and work. The lower the temperature of the borax solution the more efficient the cooling to be expected from its application to the electrodes and work. The solution must not circulate through any internal piping of the machine cooling system, because plugging of these lines with borax can result.

PROJECTION WELDING

Formation of Projections

A projection may be embossed in a sheet of metal; it may be produced on a solid piece of metal by machining; or it may be produced on an edge in a punch press in several ways. The height may be anywhere from a few thousandths of an inch to $^1/_8$ in. or more, depending upon the job. The purpose of projections is to localize the current and pressure at predetermined points. In this modification of the spot welding process the concentration of the welding current is determined by the preparation of the work-pieces rather than by the size and shape of the electrodes.

There are several advantages to be gained by the use of projections, namely:

1. The achievement of satisfactory heat balance for welding difficult combinations of metals and thicknesses.
2. More uniform results in many applications.
3. Increased output per machine because of making several welds simultaneously.
4. Longer electrode life.
5. Welds may be spaced more closely together.
6. Parts are more easily welded in an assembly fixture.
7. Finished appearance is often improved.
8. Parts may be projection welded that otherwise could not be spot welded.

1. The major portion of the heat tends to develop in the part bearing the projections during the welding operation. For this reason the projections should be produced on the heavier of two pieces of the same metal or, if possible, on the piece of higher conductivity if dissimilar metals are being joined. The reverse can, however, be used under some conditions.

2. Because uniform projections may be readily obtained on a punch press, several variables such as contact area between the parts and electrode mushrooming are avoided. Also, the surface condition of the parts does not seem to affect the welds as much as in spot welding. If a part requires several welds, they are made simultaneously, thus largely avoiding difficulties due to shunted currents as in spot welding. Both the location and strength of the resulting welds are more certain.

3. The only limits to the number of welds that can be made simultaneously are the ability to control pressure and current so that they are divided equally among the different welds and the capacity of the equipment. When several welds, from two to eight, are needed, they are usually made simultaneously. Proper division of pressure and current with projections is necessary because the currents pass through parallel paths, and the paths of lowest resistance carry the heaviest currents.

4. Frequently the areas to be joined are flat except for the projections. In such cases the electrodes are flat and large enough to contact a large area. In other

cases, when the surface to be contacted is irregular in shape, the electrode is fitted to the surface so that a high force may be applied without distorting the part, and the large current may be introduced without injuring the surface. Electrodes and dies having such large contact surfaces show less wear and hence require less attention or maintenance.

5. If two spot welds are located too closely together, there may be difficulty due to current from the second weld being shunted through the preceding weld. Since the projection welds are made simultaneously, there is less trouble from this source, but if they are placed too closely together irregular forms may lead to poor distribution of current. Ability to equalize the distribution of pressure and current, and the available size of the machine limit the arrangement and spacing of projections. However, if more than three projections are welded simultaneously, height of projections must be uniform within close limits, to avoid having some of the projections fused before others have made contact. The pulsation welding technique is useful in this case.

6. When parts are located by an assembly fixture, the fixture and work have to be moved in a conventional spot-welding machine to make successive welds. Then, frequently, additional spot welds have to be made after the fixture is removed from the parts. When using projections, the fixture may be mounted solidly on the machine. The parts are simply placed in the nest and with one operation of the machine all the welds are made at once. One part may be located in relation to the other by punching holes in one and semi-punchings in the other to match. The projections can usually be embossed or forged in the same operation.

7. Often when small parts, such as brackets or handles, are to be welded to large pieces, they are hard to locate in a spot-welding machine, resulting in misplaced spots and perhaps extruded metal. In such cases neat embossings would be less unsightly and a fitted electrode would not mark the exposed surface. Thus, projection welding results in better control of the finished appearance.

8. Thoughtful design with ingenious preparation of metal parts can make the use of resistance welding practical with its savings in quantity production of parts for which it was previously considered unsuitable. For instance, in handling heavy steel stampings, or forgings, when spot welding is out of the question, the welding pressure and current can be localized by projections, either swaged, forged or coined.

Applications of Projection Welding

As in the press working of metals, the application of projection welding is limited only by the ingenuity of the designer. The principal uses of projection welding are those in which punched, stamped or formed parts are assembled, the embossments being formed during the stamping operation. The projection is usually circular in shape, but may be of almost any consistent design. The circular shape, however, has advantages, both in welding and also in the simplicity of punch and die design.

Projection welding is also applicable to the use of screw machine parts, the projection being turned on the screw machine part by means of a forming tool. This part may be used in connection with a stamping or a flat or formed sheet, in order to obtain the assembled piece.

Cross-wire welding, which is used extensively in making wire mesh and other forms of wire products, is a form of projection welding and the general factors which affect projection welding also apply to cross-wire welding. In addition there are specialized applications of projection welding, such as welding bolts and nuts, which may be obtained with projections cold forged in place.

The methods of preparation which make projection welding possible are frequently specialized to suit particular conditions, so that only general directions can be indicated. Annular or ring projections are frequently used on screw machine parts and for applications which require a pressure-tight joint around a hole between two parts. Such preparation also gives high strength when a large stud or boss is to be applied to thin sheet material. In some applications it is preferable to form a ring type projection in the sheet, as shown in Fig. 24.

The round head of a screw, without the slot, is a good preparation for projection welding. The shoulder under the head is an advantage because it affords a bearing surface for the electrode to introduce the current near the welding point.

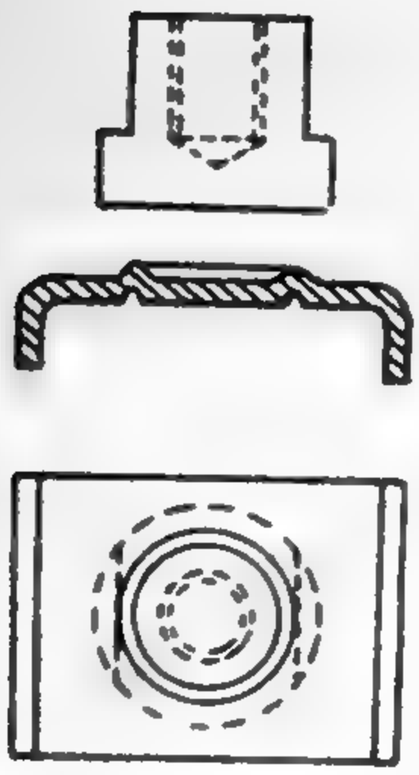


Fig. 24.—Ring-Type Embossment for Projection Welding

If there is no such shoulder on the stud near the weld, the stud should be placed in a hollow electrode that fits it closely and comes as close to the end as practical. If the current must travel through more than four times the diameter of the stud, there is danger that the stud will become overheated and collapse before the weld is completed.

Fig. 25.—Satisfactory Forms of Projections

Size and Shape of Projections

Experience has indicated that projections of the form shown in Fig. 25 are satisfactory for most work in flat or irregular stampings. Instead of being round, projections may be oblong, square, oval or any shape which may be conveniently made. With a carefully designed projection, the weld grows from the center outward and, to obtain a uniform growth, the round projection is theoretically desirable.

When projections are made on formed pieces which are circular, or not flat where the projection contacts the piece, it may be desirable to elongate a projection to make certain that proper contact is obtained. Such a design of projection for curved pieces is shown in Fig. 26. It is always desirable to start with a point or line of contact from which the weld may grow rather than to attempt to contact a plane surface against another plane surface. This latter usually results in point contact and this contact may be at some point which would not permit obtaining a complete weld.

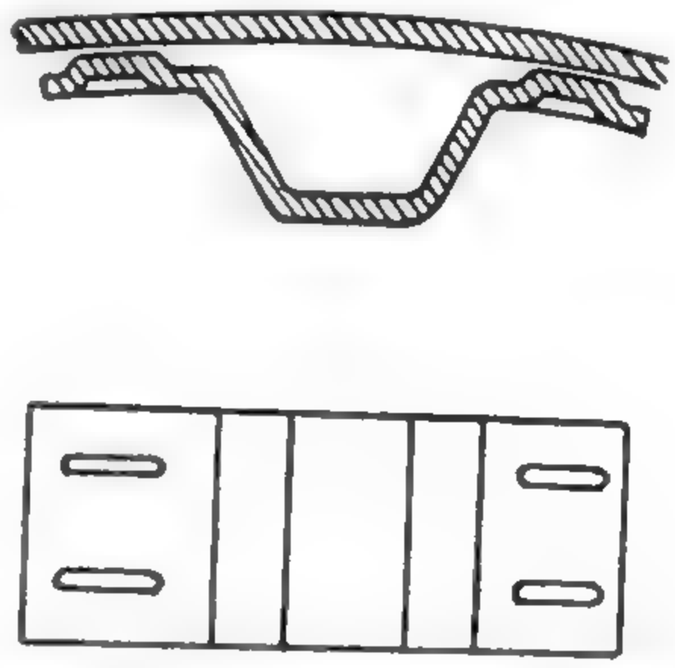


Fig. 26.—Elongated Projections for Welding Curved Pieces

The diameter of a circular projection weld may be $1^1/_2$ times the diameter of the original projection. Such projections should be domed rather than pointed.

A prick-punch may be used to produce smaller annular projections, the rim produced around the punch mark serving as a suitable projection for the welding of very thin metal to a heavier piece which carries the punch marks.

Figure 27 illustrates a screw machine

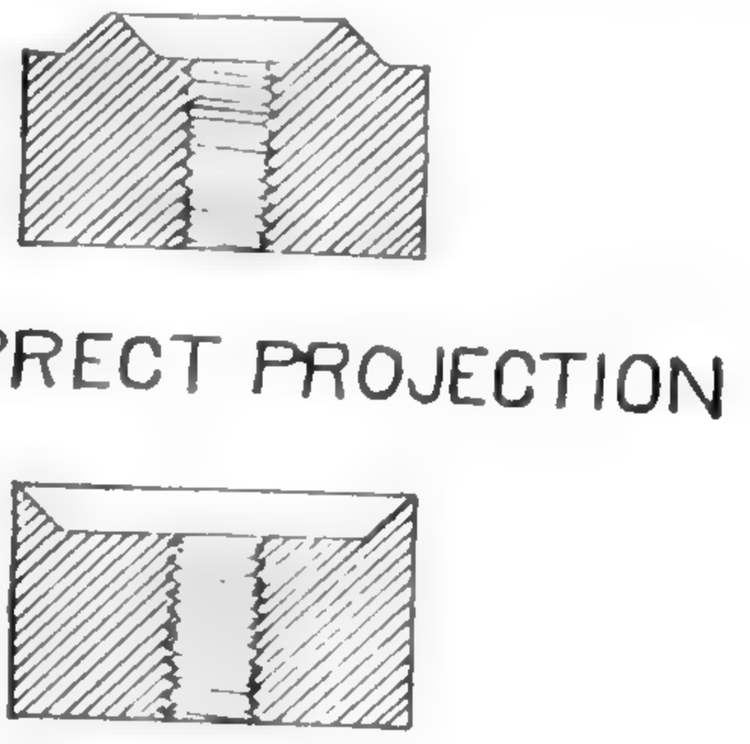


Fig. 27.—Projection for Screw Machine Products

product. If located on the very edge, the ring will squeeze out, leaving a poor weld. Annular projections may have either rounded tops or sharp 90-deg. edges (45 deg. each way). The latter design is frequently used on screw machine parts which are applied to sheet stock. The rounded top gives a better heat balance when applied to heavier parts, and is used when an annular projection is formed in sheet parts to be joined around a hole.

Although studs may be applied with annular projections as already described, domes are more often used. The dome may be on the end of the stud, or formed on the other piece at the right point. When on the end of the stud, the end is usually formed as a section of a sphere. A radius of $1^1/_2$ in. has served very satisfactorily on a wide range of stud sizes. Samples of such parts are shown in Fig. 28. Some authorities recommend that the radius of the head equal $1^1/_2$ times the diameter of the stud. Assuming no head on the stud, a weld cannot be made equal to the cross-sectional area without some material being squeezed or splashed outside this diameter.

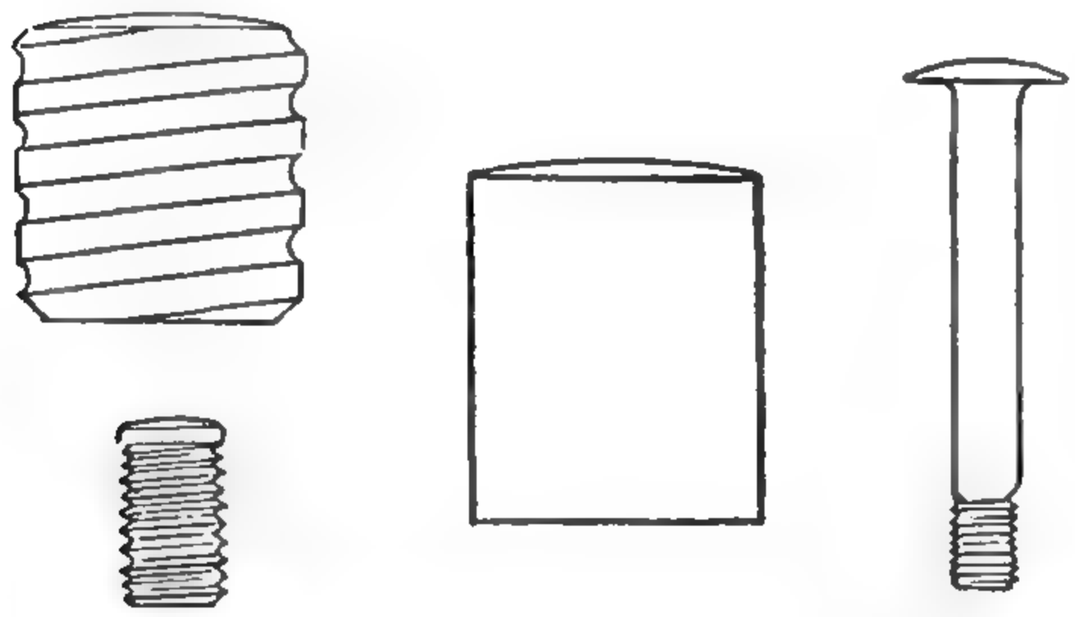


Fig. 28.—Typical Screw and Stud Parts Suitable for Projection Welding

Another advantage of the larger diameter head is that it allows an electrode-contacting surface, and also covers up any extruded metal, while facilitating a good weld for the full area of the stud. Another way to provide for the extruded metal from a smaller weld when the end of the stud is to fit down squarely and tightly to the surface, is to provide a groove around the projection to receive the excess metal.

Crossed wires make an almost ideal welding condition. Thin sheets of metal may be satisfactorily projection welded together by the use of ridges formed in the sheets. The ridges on one sheet will be parallel, but the sheet parts are brought together so that the ridges cross each other as in cross-wire welding. Single ridges may be used for a single weld or many may be used to form a mesh. This method has been used to weld handles to cans.

A projection in sheet material should meet the following requirements:

1. It should be stiff enough to support the initial force before the current is applied.
2. It should have sufficient mass to raise a spot in the plane surface to welding temperature. If too small it will collapse before the other surface is heated.
3. It should collapse without splashing between the sheets. Surfaces should be in intimate contact after welding.
4. It should not be partially sheared. Such projections may be weak and easily torn out.
5. It should be easy to form, and the punch and die should require little maintenance.
6. It should cause little other distortion of the part during forming.

When parts which span an appreciable portion of a curved surface are assembled the tendency is for the projections to slide slightly around the curved surface as they are pushed down. To avoid finishing with cold metal against hot metal at the end of the weld period, the projections for such applications are elongated as shown in Fig. 26. When parts are made in a punch press, such projections can be added for welding at slight additional expense.

A common type of preparation when a nut or bushing is to be welded over a hole is illustrated in Fig. 29. A pilot portion enters the hole to make the part self-locating, then a 45-deg. bevel meets the edge of the hole to form the weld.

Many types of studs and nuts are available on the market prepared ready for projection welding with different details. Examples are shown in Fig. 30. To weld a countersunk screw head into sheet material, four flutes or bosses are formed on the contacting surface of the head as shown in the top of Fig. 30, the sheet being punched to form a countersunk contacting surface.

Elongated projections may be used for welding box corners together. Such

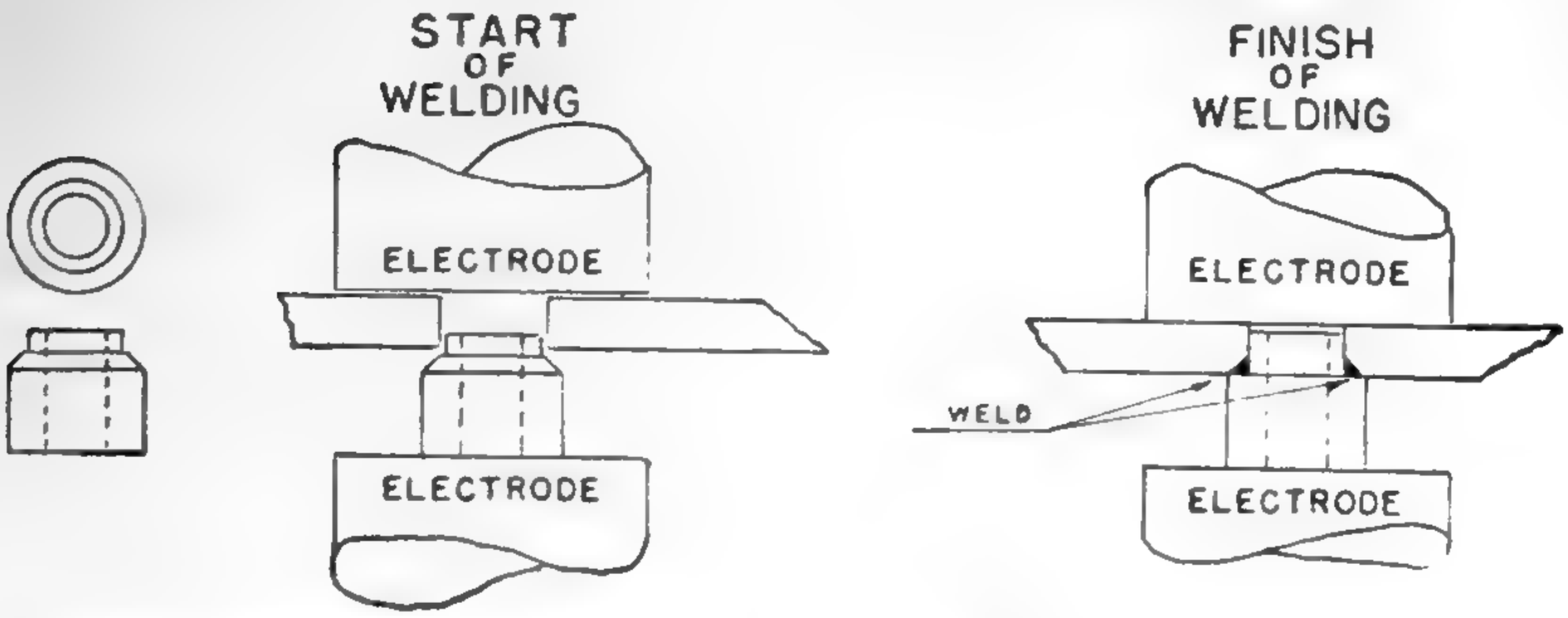


Fig. 29.—Preparation of Parts for Projection Welding Nut or Bushing to Sheet

elongations are embossed at right angles to the edge to be joined and extended to this edge. The result in this case is like welding wire sides to the edge of a sheet. An alternative method is to leave the sheets flat and in shearing the abutting part leave similarly shaped projections on the edge. These methods are also used to weld parts on edge to the center of sheet parts.

The side of a round rod is easily welded to a flat surface for a limited distance. A short piece of rod may be welded to a flat surface to serve as a stop. Part of the length of a stud may be welded to the edge of a tank and used for support or to hold a cover in place. Likewise, two flat pieces of bar stock may be welded simultaneously to the opposite sides of the end of a rod to form a clevis.

Welding Schedules

Welding Current.—The current required for projection welding per weld is slightly less than that required for spot welding.

If an annular weld is to be made, or several individual projections are to be welded simultaneously, more uniform heating results when more current is applied for a shorter time than when a longer time is used with less current. The maximum current which does not cause excessive splashing in conjunction with the proper pressure is recommended. The AWS *Recommended Practices for Projection Welding* are shown in Tables 10 to 13.

Time.—The timing of the current in

Fig. 30.—Parts Available with Welding Projections

projection welding is not so critical as the pressure, provided that the time is sufficient for the amount of current used. As the projection collapses the contact area increases, thus reducing the current density. When the projections have completely collapsed, the parts are in contact over too large an area to permit further welding. If large flat electrodes are used, the current density can result only in general heating of the work, transformer and secondary circuit. A shorter time results in higher efficiency, less discoloration and, perhaps, less distortion of the work. After the proper pressure is applied and current determined, the time should be adjusted to make the desired weld.

One of the advantages of pulsation welding is its tendency to prevent the splashing or spitting of metal, and this is especially true in multiple projection welding. Using the pulsation method a high current value can be used to get a good heat distribution, but its flow is interrupted before the points of the projections are blown off.

Frequently on such jobs, part of the projections will become heated ahead of the others. Pulsation welding allows the parts to seat themselves better after the first impulse of power, and otherwise to help set several projections down more uniformly together. Even with single projections, or in welding studs, a higher current intermittently flowing frequently produces better results.

For small studs and light sheet material, the timer is set for one cycle on and one cycle off and several impulses are used. For large studs, $^1/_{16}$-in. stock and annular machined projections $^1/_{16}$-in. high, 2 cycles on and 2 cycles off is a common setting with several pulsations. With material $^1/_8$ to $^3/_{16}$-in. thick, 5 cycles on with 3 cycles off and about 8 impulses have been used to advantage.

Force.—The pressures used in projection welding depend not only upon the material and size of projection, but also upon the design of projection and perhaps even upon the machine used. Whether the projection is embossed in a sheet or machined on solid steel, too great a pressure will cause the projection to collapse or spread out before welding heat is obtained.

On the other hand, best results require appreciable pressure, and for the best appearance embossed sheet material should be flattened out after the welding temperature is developed. It is thus apparent that pressure is a critical factor in the welding technique for a particular projection, and therefore should be set first.

If the projection is high, requiring much travel to push it down, a machine having heavy moving parts should be avoided, as the projection may melt and blow out before the machine can follow up to push it down. Quick action is needed and high inertia is a handicap that cannot be overcome by force in this case.

Electrodes.—For projection welding, the assembly fixtures usually become a part of the welding dies and machine. It is possible, with the proper fixtures, to attain accuracy with projection welding equal to that of any other assembly process.

The welding fixtures should meet the following requirements:

1. Accurate positioning of the parts.
2. Rapid loading and unloading. A jet of air will remove small parts, or a lever may be used to kick out heavier parts or the top electrode may pick up the part.
3. There must be no alternative path for the electric current. Electrical insulation must be used to insure that all the current goes through the welds.
4. For alternating current welding all magnetic iron and steel should be eliminated from the fixtures, as it reduces the electrical capacity of the machine and is apt to get hot when near the secondary loop.
5. The parts which bolt onto the top and bottom arms of the machine must register accurately like punch press tools.
6. Fixture parts which must be handled should be as light as possible. Aluminum is frequently used.
7. The safety of the operator is of vital importance.

The arrangements for welding three common types of nuts are shown in Figs. 31, 32 and 33.

When the smaller part can be placed in the bottom of the assembly fixture with the larger part on top, it is a simple matter to hold the smaller part in a recessed lower electrode. When it is desired to locate a small part on top of a larger part, it becomes more of a

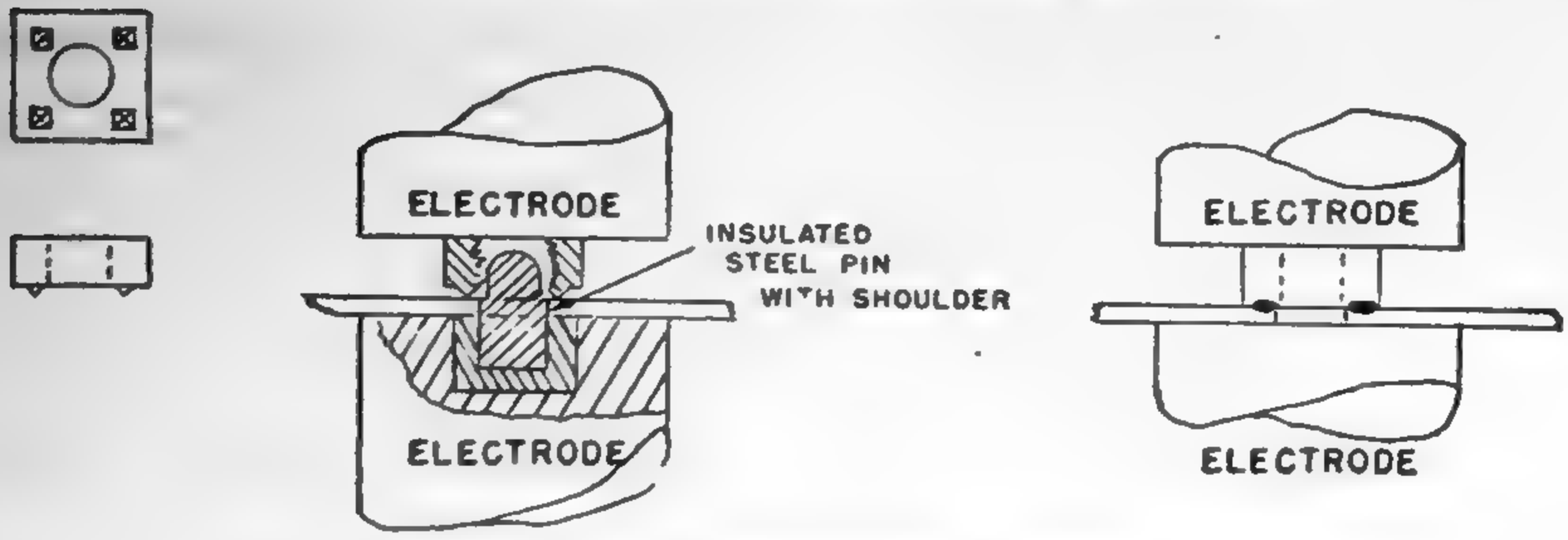


Fig. 31.—Use of Insulated Pin as Locator

problem. Sometimes the small piece can be located and held by a removable device while a flat upper electrode makes the weld. Parts that nest into the upper electrode may be held by spring clips assembled either on the outside or interior of the electrode. That is, a ball or plunger pressing against one side of the part and backed up by a spring, all assembled in a drilled hole through the side of the electrode, is sufficient to hold small parts (see Fig. 33). Vacuum is also used to hold small parts in the upper electrode.

The harder electrode materials are usually used for the construction of projection welding dies. Dies for large production or really severe requirements often have inserts of RWMA Group B material at the points of greatest stress. At other times it is cheaper and satisfactory to make the whole electrode of one piece of RWMA Group A, Class 3 material.

Heat Balance

This problem may become complicated in projection welding. It is possible to melt the projection away from one piece without bringing the mating surface to welding heat thus resulting in no weld being formed. The factors affecting the heat balance are:

1. Design of the projection.
2. Thickness of the parts.
3. Die material backing up the weld.
4. Conductivity of the metals being welded.
5. Rate of heating.

An undesirable condition exists when a massive steel part is projection welded to thin sheet steel. A projection in the thin sheet would not heat a spot in the massive part sufficiently, and the usual water-cooled, copper electrode will retard the thin sheet from heating if the projection is on the heavy piece. This condition is alleviated by using one of the hard electrode materials of low electrical conductivity to back up the sheet material.

When two different metals are to be projection welded together, the projection should be formed on the material of higher electrical conductivity, other things being equal. Higher electrical conductivity also means higher heat conductivity, therefore the speed of heating becomes a factor.

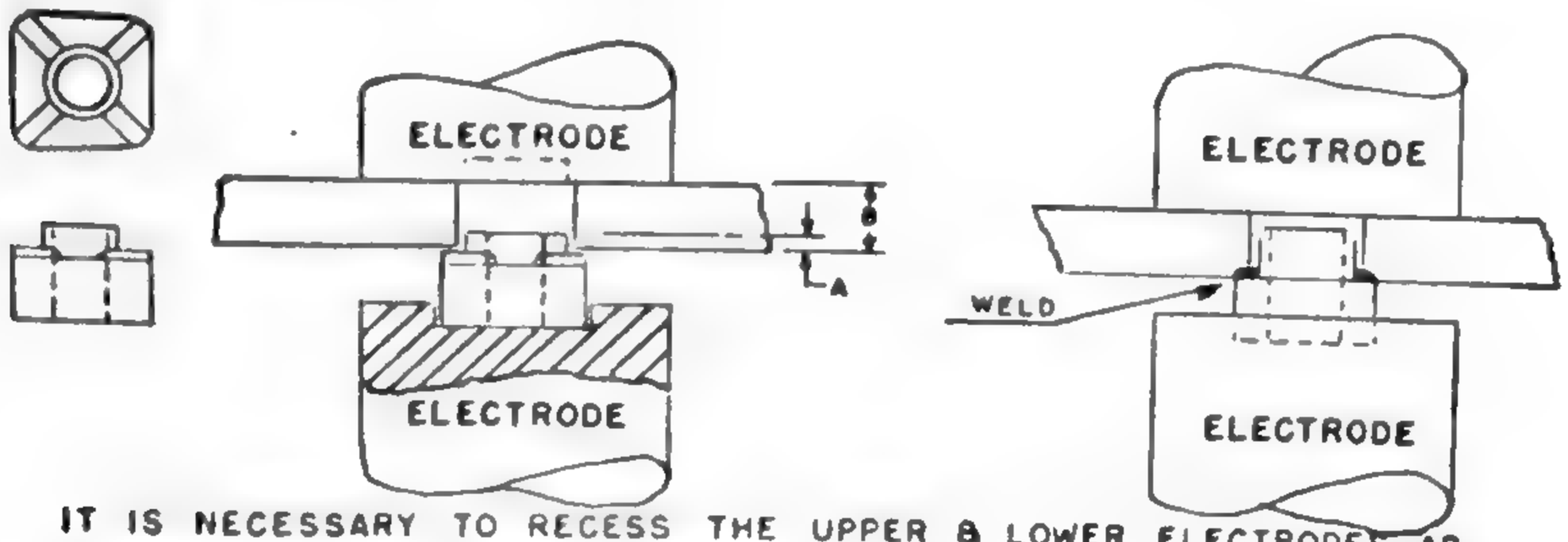


Fig. 32.—Use of Recessed Electrodes

The important principle is that the two mating surfaces must be brought to the welding temperature at the same time. Sometimes it is advantageous to put projections on both parts located so that projection meets projection. In special cases where there is a question about which piece should carry the projections, it may be advisable to make samples and try all three ways.

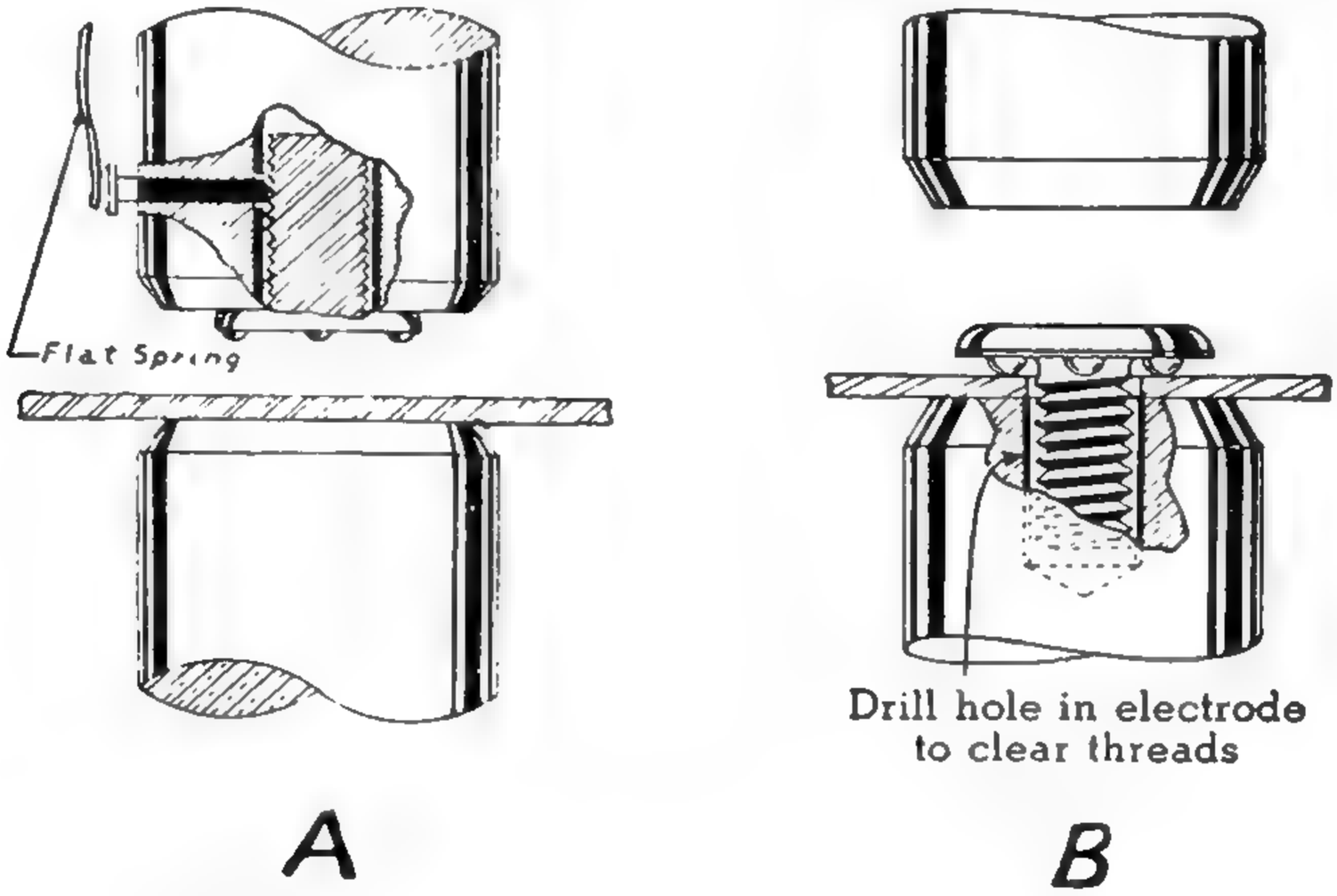


Fig. 33.—Methods of Accurate Location of Projection Welds Between Bolts and Sheet

Not all metals can be projection welded. The metal must be strong enough to support the projection. Some brasses do not lend themselves to this welding process, as the projections collapse too rapidly under pressure. Copper is considered unweldable by this process. Aluminum has been welded to a limited extent, the best results having been obtained with extruded parts. Coated stock, such as galvanized iron, terne plate and tin plate, is being successfully welded. It is also possible, in some cases, to weld dissimilar metals, such as steel to brass and steel to bronze. These latter materials require more current and shorter time for successful welding than are required for steel. Thin steel sheets are more readily spot welded than projection welded, due to difficulty of maintaining exact and small projections in this material.

EFFECT OF PROCESSES ON MATERIALS

Physical and Metallurgical

Warpage, Shrinkage and Distortion.—Spot, seam and projection welding involve the localized heating of a metal to its melting point under the pressure of shaped electrodes. During the making of the weld its volume is surrounded by unheated metal. The metal at the interfaces, being at the highest temperature, has the lowest strength. The tendency of the exterior work parts to bend around the impressing electrodes is always present, and for soft metals under excessively high electrode pressure even the cold metal is deformed prior to the application of the welding or preheating currents. The tendency to deform is greater with heated metal. Steeply faced electrodes and higher forces both tend to increase distortion.

Several factors besides the actual welding setup affect the appearance and quality of the finished product. In seam welding, more than in any other resistance-welding process, warpage must be prevented as far as possible. It is impossible to give specific universal cures for warpage, but an understanding of the causes will enable the designer and operator to reduce it to a minimum. In general, warpage is caused by the non-uniform contraction of the cooling metal which is surrounded by unheated metal. The unheated metal tends to retain its original dimensions; the heated metal cools to dimensions less than the original. This induces differential stresses which cause or tend to cause movement. When many seams are used on a single assembly, the welds can

sometimes be staggered so that the warpage from one seam will offset that from another. For instance, when welding the bottom of a rectangular box, the welds should not be made in continuous rotation but on one side, then on the opposite. When several parallel seams are made as in evaporators or condensers, simultaneous welding of all seams on special machines will usually reduce the warpage to a negligible amount. Sometimes, on long seams, it is necessary to resort to skip welds, that is, weld a short length, skip a portion of the seam, weld another short length, skip again, etc., then in a second pass over the seam complete the unwelded portions. Peening of spot, seam and projection welds in long flat sheets will also relieve warpage.

The most effective means of eliminating warpage in seam welding is the use of flood cooling. Most common practice is to use a jet of cooling water immediately before and after the weld on both sides; four jets in all. Each jet should be regulated by an individual valve and come from a nozzle of copper tubing about $^{3}/_{16}$-in. diam., impinging on the work just as closely as possible to the weld. The weld line is hot for some distance from contact with the electrodes. The length of this *tail* depends upon stock thickness, speed of operation and other factors. The jets should be adjusted to keep this tail as short as possible because this determines to a large extent the amount of warpage.

Residual Stresses.—Stresses of undetermined magnitudes result from cooling of the welds. These stresses result from differential heating and cooling and are of sufficient magnitude to contribute to distortion of the structure. They may be compensated for by arranging the order of welding in continuous symmetry about the center of the parts. Low temperature stress-relief and peening may be desirable in special cases to relieve residual stresses. Jigging the parts under stress prior to welding tends to reduce the final stresses. A more complete discussion of shrinkage and distortion will be found in Chapter 43.

Metallurgical Effects.—The rate of quenching spot welds is extremely rapid in the thinner members where the liquid-cooled electrodes are nearest to the weld center, and the total quantity of heat is a minimum due to the short welding times and small weld volumes used. As longer times are employed on thicker members more heat is dissipated into the surrounding metal and since the quenching potential of the electrodes is also at a minimum, the cooling rates for these conditions are a minimum. In short time projection welds, severe solid metal quenching is obtained, and such techniques may be employed in thicker members. Quench rates for spot, seam and projection welds under some conditions may be so severe that even for low-carbon steels the fully hardened condition is achieved. It is for this reason that the *Recommended Practices* limit the carbon content of plain carbon steels to 0.15% max., unless special techniques are employed. The metallurgical result in resistance welding is the same as if the base metal were heated to or above the melting point for a short time and quenched under pressure at a corresponding rate. Although the quenching rate may vary, depending upon the welding conditions employed, its effect on the microstructure of the alloy is equivalent to the most drastic quenching methods employed in modern heat-treating practice.

Welds in low-carbon steel withstand the rapid quench without embrittlement only because the carbon content is below that required to produce a brittle structure. Aluminum alloys, copper alloys and magnesium alloys are not quench hardenable, since quenching retains the alloying elements in solid solution. Hardening is achieved by a heat treatment that produces precipitation of the alloying element in a compound form. Stainless steels are not quench hardenable or precipitation hardenable, but derive their higher mechanical properties from cold working. Accordingly, heat-treating welding techniques reduce the mechanical properties of these metals in the weld area.

For the higher carbon and quench-sensitive alloy steels, special quench and temper techniques have been developed which improve the ductility and toughness of the welds without the need for subsequent furnace heat treatment. These welding procedures involve making of the weld and allowing it to quench under pressure. Enough time under pressure is allowed to permit transformation of the metal constituents into martensite and then a lower level current is applied, the function of which is to reheat the marten-

site to its tempering temperature. The weld may then be rapidly cooled. Tempered martensite is known to be one of the toughest structures. Tempering in the welding machine does not allow enough time to develop a fully tempered structure, since the tempering of martensite is a time-temperature process wherein the time required is much longer than the time required for welding. Tempering in the machine is applicable where the initial quench rate is sufficiently rapid to cool the metal faster than the critical rate, thus assuring the formation of the martensite. It is therefore most readily applicable to thinner spot-welded sheets and to projection welds on heavy members.

With sequencing controls it is possible to work out various combinations of preheating, welding and post-heating techniques for use in welding special metals or combinations of metals to produce desirable microstructures.

Surface Appearance.—Surfaces of spot and seam welded parts are always subject to indentation and marking on at least one side. It is usually possible to make welds without such surface markings on one side by using a flat electrode on that surface. Sometimes a concave electrode is employed for thin parts and the resultant raised surface is later ground flush. The use of improper machine settings and electrode dressing will result in welds as shown in Fig. 16. Electrode marking becomes pronounced after the parts are painted because of the structural change of the metal under pressure even though no surface distortion takes place.

The surfaces of coated materials are partially destroyed during the welding operations. If corrosion is of prime importance it may be desirable that the parts be welded prior to coating. However, some coatings do not require full coverage to give protection.

Weld, Joint and Structure Quality

High quality joints can be consistently produced using proper designs and welding procedures. As for all welding processes the properties obtained depend upon the specific metal being welded. It is essential that in spot welded joints the schedules be adjusted to compensate for current shunting losses through prior welds, or the design be adjusted to fit the particular schedule available. This is important for all materials, and is particularly appropriate for those metals or combinations of metals, for which proved standard Recommended Practices are not available.

Weld Diameters.—The average weld size recommended is three times the thickness of the thinnest outer piece, plus 0.06 inch. The specific sizes vary for each metal. The weld sizes are derived from a consideration of achieving the highest average unit shear stress at failure, without producing inconsistent welds. In projection welding the size varies to suit special conditions but in general the diameter of the final fused zone is maintained the same as for spot welding.

Weld Properties.—Structures employing spot and projection welds are usually designed so that the welds are loaded in shear when the welded parts are stressed in tension or compression. For the more commonly used metals, welded joints stressed in this manner will develop the full tensile strength of a strip of the base metal for a width somewhat greater than that of the weld diameter. The ratio of that width to the weld diameter can be taken as a criterion of weld quality for a given material. The direct tensile strength of spot and projection welds is somewhat less than the strength in shear for ductile welds and very much less for non-heat-treated welds in hardenable materials. The variation in this ratio is so pronounced that the ratio of direct tension to tension-shear strength is commonly taken as a criterion of weld ductility. Untempered welds in hardenable but stronger metals may be weaker in direct tension than those in less strong ductile metals which are not as susceptible to quenching. The strength of welds increases with increased diameter although the average unit stress decreases. The second relationship is caused by the increasing tendency of failure to occur at the edge of the weld due to stress concentrations, as weld size increases. This factor makes an expression of average unit shear strengths for spot, seam and projection welds in any material meaningless unless the weld size is specified. For example, in low-carbon steel the calculated average shear stress of good welds at rupture will vary from 10,000 to 60,000 psi., the low values being obtained in thin sheets where relatively large welds are employed and the high values for relatively small welds. In both instances the actual

tensile stress in the material at the weld periphery is at or near the ultimate of the unwelded base metal. This factor tends to cause the shear strength of circular welds to vary linearly with diameter.

Spot and projection welds are not strong in torsion where the rotational direction is in the plane of the welded part, and the weld diameter is small. This strength tends to vary with the cube of the diameter and larger welds are therefore much stronger in torque than small welds.

Little torsional deformation is obtained from brittle welds prior to failure. Angular displacements from 5 to 180 deg. are obtained when varying from extremely brittle to very ductile welds. This spread provides the basis for using torsion loading as a test method.

All weld properties are dependent upon the prewelded temper or strength and the composition of the unwelded base metal. In all cases where the quenched metal responds to temper treatment, the weld properties also respond in like manner, the improvement being of a high order in the case of such materials as high-carbon and alloy steels.

Weld Penetration.—Penetration into the base metal is ordinarily permitted to vary from 20 to 80% of the thickness of the outer member. Full penetration is unsightly and also denotes a condition which results in low electrode life. Too little penetration denotes inadequate heat or heat balance and inconsistent weld quality. Desirable and undesirable weld sections are shown in Chapter 42.

Weld Symmetry.—Welds should preferably be symmetrical about the plane of the faying surfaces.

Cracked Welds.—Cracked welds are the result of overheating, improperly applied loading during welding, or the use of improper schedules on crack sensitive materials. Quench cracks at the weld periphery are particularly damaging since this is the zone of highest stress, whereas those at the weld center usually have no significant effect upon the weld properties.

Porous Welds.—Most commercially produced welds contain some center porosity, usually the result of overheating, inadequate pressures, the premature release of an adequate pressure or too late application of an adequate forging pressure. Weld center porosity has no demonstrable influence upon weld properties since the applied stresses are concentrated near the periphery of the welds. It can be eliminated or reduced by using lower rates of heat build-up, lesser maximum temperatures and higher pressures.

Weld Consistency.—The consistency of weld quality is determined by the uniformity of the thickness, material composition, surface conditions and temper of the materials being welded; the consistency of the mechanical-electrical operations of the equipment; electrode maintenance; and the choice of welding schedule.

Since the weld properties are a function of the thickness, composition and temper of the metal being welded, the most perfectly operative equipment cannot produce welds of a higher order of consistency than that of the metal furnished to the welding electrodes. Of the welding variables, the magnitude of variation in surface conditions and secondary current are the most important as previously discussed. As a practical matter variations in alternating current are serious because current tends to fluctuate with line voltage variations, varying amounts of magnetic materials in the throat of the welding machine and variable shunting effects. However under proper control there is little difficulty in maintaining high shear strength consistencies.

Surface Indentation.—Surface indentation may be held to negligible magnitudes by the use of flat electrodes on the one side while the electrode impression on the opposite side of the joint may be held to 5 to 10% of the individual member thickness, as desired. Indentation is increased by the use of excessive heat, excessive force and the use of steeply-faced electrodes. (See Chapter 42.)

Surface Melting and Electrode Pickup.—Surface melting of the parts, exclusive of coatings, is the result of insufficient pressure or insufficient time with excessive current, or a combination of both. The use of inadequate electrode cooling and inadequate squeeze and hold times also contribute to this difficulty. Electrode pickup is particularly pronounced when welding refractory metals in air with copper-alloy electrodes.

Sheet Separation.—Excessive sheet separation results from the same causes as surface indentation, to which it is related. A steeply tapered electrode applied under high pressures on the exterior of a sheet having a highly heated interface acts as

a male punch. It tends to depress the exterior of the sheet and raise the interface radially about the weld periphery.

Interface Expulsion.—Expulsion is the result of overheating, particularly when combined with inadequate pressure or steeply-faced electrodes. It results in internal cavitation and usually reduces weld strength. This tendency is so pronounced that it is a general operating rule to apply such a current that expulsion is just avoided. Experience indicates that the resultant weld will then have maximum shear strength for the force-time-electrode conditions used.

Edge Distance.—Edge distance must be sufficiently great to provide adequate heat conduction between the weld periphery and the edge of the work-part and adequate strength to resist the lateral forces of deformation. Values required vary with the material, weld size, sheet thickness and schedule used. Appropriate values for different metals, measured from the weld center, may be derived from the *Recommended Practices.* Fig. 34 shows the results of proper and improper edge distance.

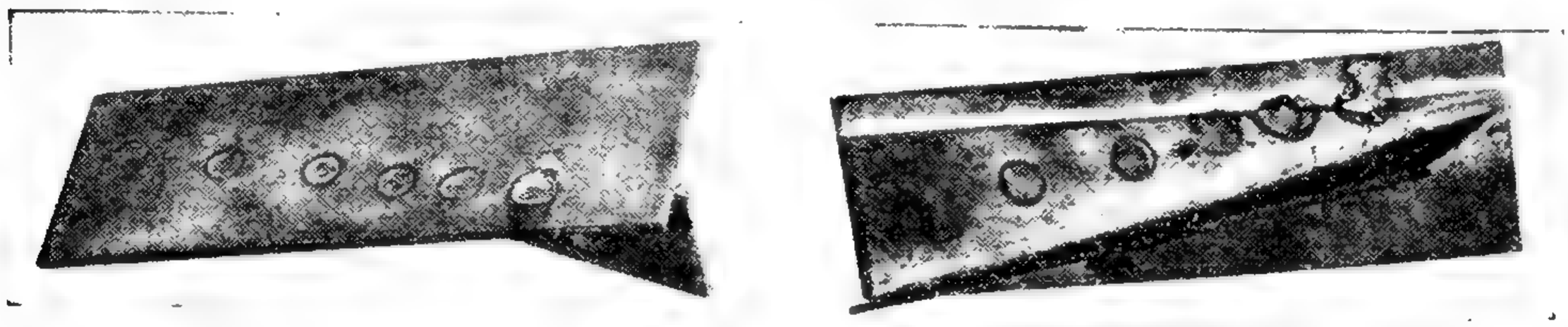


Fig. 34.—Effect of Insufficient Edge Distance

Contacting Overlap.—The contacting overlap cannot be less than twice the minimum required edge distance, measured from the center of the weld. Values for different metals are given in the *Recommended Practices.*

Electrode Clearance.—Sufficient clearance must always be provided to permit entry of the electrodes. Values for this dimension are considered in the *Recommended Practices* in specifying the given values for contacting overlap. See Fig. 35 for illustrations of proper and improper electrode clearance.

Joint Properties.—Properly designed and welded joints can be furnished in some cases to develop the full tensile strength of the unwelded base metal when so desired. When joints of lesser strength are required it is more economical to provide a minimum number of welds.

The use of a single row of welds results in more angular deflection of the joint, under high loading. This causes a higher direct tensile component to be applied to the weld edges, thus further tending to reduce their strength. Multiple rows of welds reduce their deflection tendency and permit wider weld spacings with reduced shunting, but require a greater overlapping of material.

Spaced, Tangent, Overlapped and Seam-Welded Joints.—For those metals in which a spot or projection weld loaded in shear will develop the full strength of a strip having a width greater than the weld diameter, it is obviously not necessary to space the welds closer together than the developed strength ratio in order to provide a joint of the full base metal strength. Closer spacings are required only when seam tightness is required. Since closer weld spacing contributes to current shunting losses it should never be held closer than necessary to provide the required total joint strength.

QUALITY CONTROL

Quality cannot be directly inspected or tested into the final product. Control of weld quality is maintained only by precontrol of the factors which tend to produce variations in the final product, including design; material thickness, composition, temper and surface conditions; welding factors as electrode size, shape, cooling conditions, and rate of approach; imposed pressures; secondary current; squeeze, current and hold times; fit-up of parts; and selection of welding methods and schedules which have the lowest reactions to known variations.

Controlling the flow of materials to the welding machines is an individual

problem, and the means for doing this are outside of, but pertinent to, welding.

Eletrode Maintenance.—Maintenance of electrodes is necessary for the production of strong, consistent welds. Allowing electrode deterioration to proceed until welds become unsatisfactory is poor and non-permissible practice. Abnormal increases in the size of contact area should be regarded as a danger signal to weld strength and quality. If a 1/4-in. diam. electrode face is allowed to increase to 5/16 in. by mushrooming, the contact area is increased 50%, with a corresponding decrease in current and pressure densities. Depending somewhat upon the schedule being employed, the result may be weak welds or defective welds. A danger sign is the production of poorly shaped spots, which may be caused by:

(*a*) Non-circular outline of tip face.
(*b*) Use of too large a flat face on the tip.
(*c*) Use of flat tip with blunt and irregular edge.
(*d*) Concavity or convexity of the tip.
(*e*) Failure to maintain tips parallel to the work.
(*f*) Misalignment of electrodes.

Correct alignment is relatively easy to maintain when stationary welding machines are used, but with gun-type machines lack of alignment is common, and will be more or less serious depending on the ease of manipulating the equipment for the particular application. Therefore it is to be expected that the same electrode will have longer life between dressings on positioned work (stationary machines) than on non-positioned work (welding guns).

The success of projection welding operations in production depends largely on three factors as far as electrodes are concerned:

(*a*) Proper selection of materials.
(*b*) Proper installation.
(*c*) Proper maintenance.

Assuming that the dies are of correct design and construction, the installation is next in importance. First, the platens of the machine should be carefully checked to make sure that they are level and at right angles to the motion of the ram. The platens must also be smooth and clean; free from dirt, nicks, pit marks, etc. If these conditions are not met the platens should be removed and machined before any attempt is made to install the dies. The check for parallelism of the platens should be made under normal operating forces. This can best be done by inserting a steel block with known smooth and parallel faces between the platens and checking with feelers. Another good check is to place tissue paper under the corners, then feel for looseness. Prussian blue may be placed on the block to register on the paper. However, never allow Prussian blue to get on the platens, as it is difficult to remove and can start corrosion of the platens.

Next, check the base of the die blocks. They must be clean, smooth, level and free from burrs and nicks. If not, a machine cut should be taken. Silver plating of contact surfaces is often desirable since silver oxide is an electrical conductor.

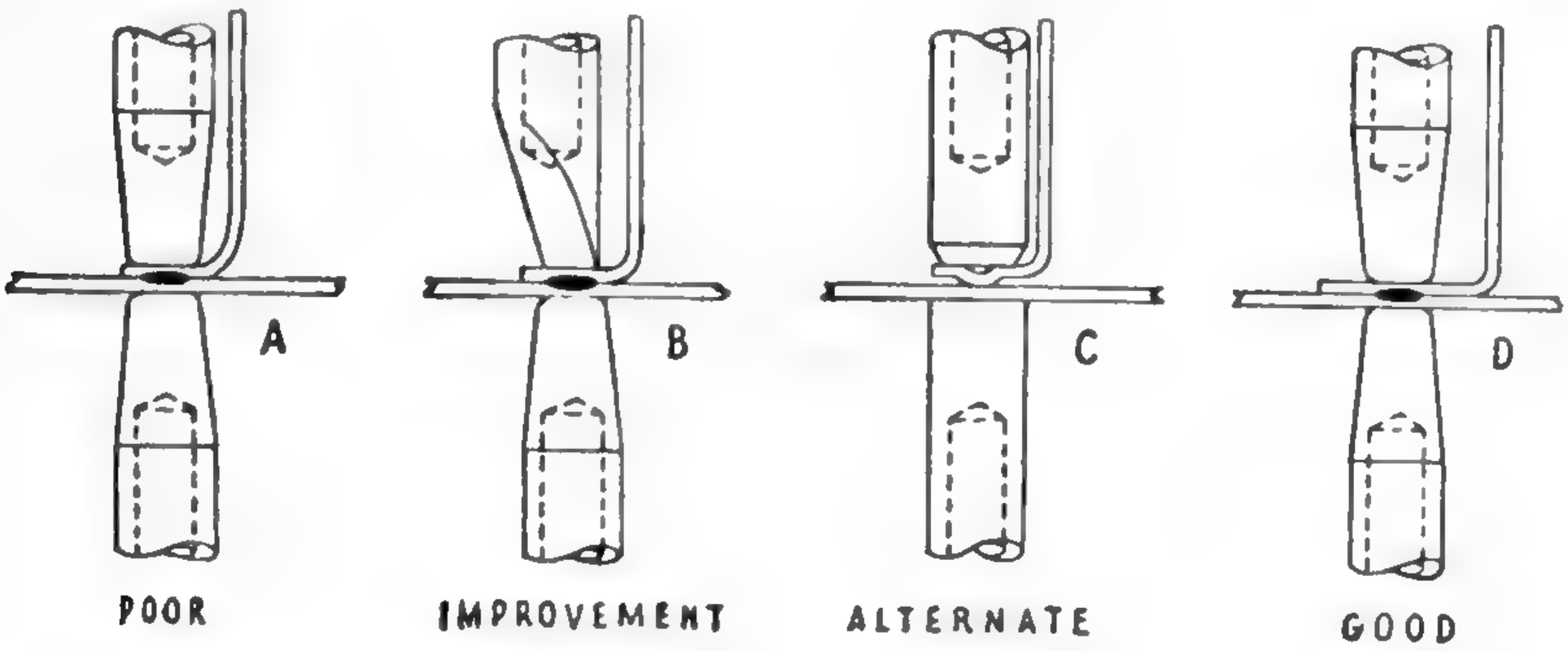


Fig. 135.—Proper and Improper Electrode Clearance

The dies can now be installed in the machine. Most machines have tee slots in the two platens cut at right angles to one another to permit universal alignment of the dies. When they are properly lined up they should be bolted down securely. With the work in place, the ram or knee, whichever is adjustable, should be adjusted for the proper stroke, making the necessary allowance for upset of the projections.

If the faces of the projections are all in one plane, and if they have been checked for uniform height, it now can be assumed that the setup is ready for trial welds. If the trial indicates nonuniformity of current or pressure, before attempting to correct the dies make sure that the trouble does not lie elsewhere such as in shunting of current through locators, unequal distribution of current caused by some projections being considerably closer to the transformer than others, too much play in the welding head or too much deflection in the knee.

The use of shims between die components or between dies and platens is to be avoided as much as possible. When shims are used they must be only of clean, high-grade soft copper sheet and with sufficient area to carry the secondary current.

If the projections are located on curved or angle surfaces, accurate templates should be provided for checking the dies, keeping in mind that the final proof of the setup is the actual weld. Also, when welding curved surfaces, or two or more pieces to other parts, difficulties may be encountered on account of the manufacturing tolerances of the metal thicknesses involved. There is no cure for this condition except to provide for it in the design of the parts and arrangement of projections.

Dies can usually be reworked readily in the machine without disturbing the setup if the reworking is of a minor nature.

Welding Variables.—For a given uniform material fed to a suitable machine operating under a recommended schedule the matter of producing good welds consistently becomes a routine matter. Uniform production welding is therefore the problem of assuring that essentially constant conditions are provided. When the electrodes are maintained as to size, and the force, time and current delivered to the weld zone are also maintained constant there is no possibility of single weld quality variations. Since, as a practical matter, it is impossible to achieve absolute uniformity in production schedules they always should be set up to allow for some variations without causing significant variations in weld properties.

Electrode force is usually checked from air or hydraulic pressure vs. force calibration curves, but facilities should be available to check the actual force as required. In general, only static forces are measured. Proper maintenance and lubrication of moving parts help to assure uniformity of dynamically applied forces. Periodic checking of electrode contour and shape, followed by lathe dressing as required assures the application of uniform pressures and current densities. Delivery of constant currents to the weld interfaces can be assured by the use of current or voltage regulators, maintenance of proper line voltage, fit-up of parts, proper spacing of welds and by adjusting for magnetic materials introduced into the secondary loop of the machine.

Sampling Methods.—A method of sampling employed under some specifications is to provide test welds at the beginning of welding each part and at the beginning of each subsequent hour of work and for each shift and electrode change. Usually the tension-shear test is the only test made at these intervals. In some instances macroetching is employed to provide a check on weld diameter, penetration and symmetry.

Testing Methods.—Details of the accepted methods of testing are described fully in Chapter 42.

COMMON APPLICATIONS

Metals

Most metals and their alloys can be welded to themselves and often to each other by spot, seam and projection welding. Electrical and thermal conductivities generally go together and for high conductivity metals, as copper and silver, even with high currents, little heat is generated and much of this is rapidly dissipated into the surrounding metal. For these metals therefore short welding times must be employed; the heat energy must be rapidly applied. This means the use of high currents. The total heat energy required to reach the melting point is a function of

the product of the specific heat, the melting temperature and the density of the metal.

For hard metals, such as cold-rolled, stainless steels, high pressures may be employed and soft metals, such as lead, require the use of low pressures. Also for the softer metals larger radii, domed electrodes or smaller face angles on the electrodes are required to prevent piercing of the molten pool.

The final weld properties are independently determined by the characteristics of the metals being welded or by the resultant alloy combination formed.

Alternating current is most widely employed for ferrous metals and direct current for nonferrous metals but either may be welded with either type of current.

More detailed descriptions of welding process data for each type of metal are given in the appropriate chapters.

Iron.—Commercially pure or *ingot* iron results in very ductile welds which have somewhat lesser strengths than steel due to the lesser strength of the base metal and to a lesser hardening of the weld ingots. See Chapter 27.

Steel.—Plain low-carbon steels, up to about 0.15% carbon content, are readily and widely welded. For higher carbon contents, the use of special welding techniques involving *in the machine* heat treatments are recommended. More complete data are given in Chapter 27.

Low-alloy steels may be spot welded with or without the use of special heat-treating techniques, depending upon the physical properties desired. More complete details are given in Chapter 29.

Austenitic steels are non-hardenable and the severe quench involved is not detrimental for these compositions. They are therefore readily spot, seam and projection welded. More complete descriptions of their welding characteristics are given in Chapter 31.

Aluminum and Aluminum Alloys.—All of the commercial aluminum alloys which are produced in the form of sheet and extrusions may be welded provided the thicknesses involved are not too great. The provision of proper equipment for making the welds, the preparation of the surface of the material for welding and the use of correct machine settings are necessary for producing satisfactory welds.

Aluminum and aluminum alloys have comparatively high thermal and electrical conductivity, and in order to make spot and seam welds, high values of welding current and relatively short welding times are necessary. A further factor which influences the choice of equipment for spot welding aluminum is the rapid softening of the material at the welding temperature which necessitates a slight movement of the welding electrode into the material being welded. While this movement is small it must take place in a very short time, perhaps 0.002 to 0.005 sec., and as a consequence, considerable acceleration of the welding electrode assembly is necessary if contact is to be maintained between the welding electrode and the material welded. For this reason, the moving electrode system should possess low inertia and should be so guided as to minimize friction. More specific details are provided in Chapter 32.

Magnesium Alloys.—Magnesium alloy sheet and extrusions are commonly spot welded, after properly cleaning the surfaces. More information on the welding of these alloys is given in Chapter 33.

Copper and Copper Alloys.—Copper is one of the most difficult of all metals to resistance weld because so little heat is developed and that heat is conducted away so rapidly. It is precisely this characteristic which has resulted in the widespread use of copper as an electrical current-carrying material. The introduction of alloying elements increases the electrical resistance, decreases the thermal conductivity, reduces the melting point and increases the ease of welding. A more complete discussion of these alloys is given in Chapter 34.

Zinc.—Zinc alloy die castings have been experimentally welded by the spot, seam and projection welding processes, using synchronous electronic controls. Spot welds of adequate strength and liquid-tight seam welds have been produced. See also Chapter 36.

Lead and Lead Alloys.—Pure lead and the lead alloys can readily be welded. Large body diameter electrodes are recommended with about 2 deg. face tapers. This is necessary to prevent the electrodes from passing entirely through the almost strengthless molten weld zone. Welds in lead are highly ductile; those in some of the lead alloys are brittle, as described in Chapter 36.

Silver.—Silver, having the highest electrical and thermal conductivities, is diffi-

cult to weld. It may be readily brazed.

Nickel and Nickel Alloys.—Nickel and its alloys are readily spot, seam and projection welded. Additional discussion of these alloys will be found in Chapter 35.

Molybdenum.—Molybdenum can be welded with some difficulty. Best results are obtained by roughening the interfaces to form a multitude of small projections. The major difficulty is electrode maintenance. Copper alloys do not maintain their shape or contacting area and tend to deposit metal on the outer work surfaces. To prevent this tendency the sheets are sometimes welded under water. The final welds are brittle.

Tantalum and Tungsten.—Tantalum and tungsten may be welded in about the same manner as described for molybdenum.

Coated Materials.—Electroplated steel has a lower total electrode-to-electrode resistance than ordinary surfaces of the same metal and correspondingly higher currents are required in the welding of these materials. Terne plate, tin plate, galvanized (zinc) coated, aluminized and cadmium-plated steels are readily welded. Coatings are commonly damaged or destroyed in the welding process and therefore nickel and chromium plated steels are not ordinarily welded, since these coatings are usually applied for appearance only.

Dissimilar Combinations.—In general, any combination of metals which alloy together can be welded. The resultant properties, however, will also be determined by the reaction of the resultant alloy. Each of the many possible combinations must therefore be judged on its merits, while considering the requirements of the specific product.

Products

Resistance welding is a far more flexible method of joining metals and is applicable to a greater range of sizes, shapes and materials than is generally appreciated.

Typical resistance-welded products which have been in production for many years serve as a general index of the possible uses of resistance welding. The following list gives some of the applications which are found in several of the important metal fabricating industries:

Aircraft.—Fuselage, landing gear, mounts, guards, exhaust rings, wing assemblies, tail assemblies, wheels; more complete details are given in Chapter 55.

Automotive Products.—Bodies, cabs, frames, seats, brackets, levers, pans, wheels, housings, supports, shock absorbers, mufflers, rims, ignition parts, grease guns; in fact the modern automobile is essentially a resistance-welded structure made up of thousands of individual welds. More complete details are given in Chapter 54.

Building Construction.—Trusses, partitions, moldings, sash, gutters and drains, ornamental iron work, signs. See Chapter 47.

Communications Equipment.—Telephone and telegraph equipment, magnets, jacks, instruments, switchboard parts, coin boxes.

Domestic Goods.—Furniture, sewing machines, vacuum cleaners, stoves, cutlery, tableware, ashcans, cooking utensils, irons, lamps and shades, lawn mowers, pails and buckets, spray guns, wire goods.

Electrical Equipment.—Enclosures and receptacles, rotors, contact points, electronic tubes, appliances, transformer tanks, cabinets, switchgear, switches, cable connectors, relays, control instruments, measuring instruments, meters, armatures.

Hardware.—Trunk and suitcase hardware, skates, hand trucks, pulleys, tool handles, shovels, rakes, hoes, wagon and truck hardware, tanks, sporting goods.

Industrial Equipment.—Stokers, utility baskets, bins, pallets, rings, crates, cabinets, stands.

Miscellaneous.—Carbon and alloy steel tubing, fabricated tubular parts, camera parts, jewelry, surgical and dental instruments, farm implements, bicycles, finned tubing, photographic equipment, optical goods, fountain pens.

Many of the applications listed do not refer to complete products, but rather to product parts. In numerous instances it is found advantageous to combine resistance welding with other joining methods. For example, spot welding may advantageously be used for tack welding of assemblies that are to be arc welded; also, spot and projection welding are frequently used to join parts for furnace brazing.

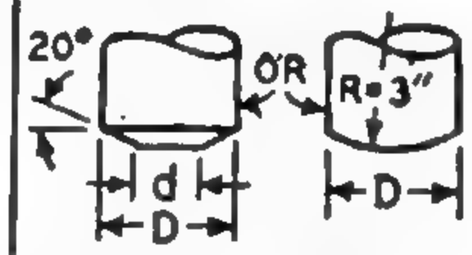
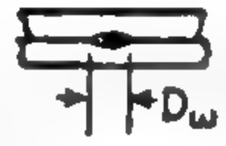
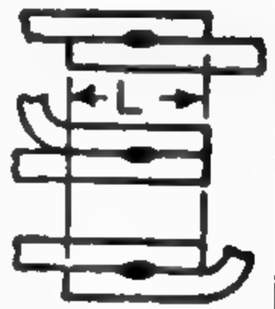
Table 1—Recommended Practices for Spot Welding Low-Carbon Steel

THICKNESS "T" OF THINNEST OUTSIDE PIECE (NOTES 1, 2, 3 AND 4 BELOW)	ELECTRODE DIAMETER AND SHAPE (NOTE 5 BELOW)		NET ELECTRODE FORCE	WELD TIME (SINGLE IMPULSE)	WELDING CURRENT (APPROX.)	MINIMUM CONTACTING OVERLAP	MINIMUM WELD SPACING (SEE NOTE 6 BELOW)	DIAMETER OF FUSED ZONE	MINIMUM SHEAR STRENGTH LB.		THICKNESS "T" OF THINNEST OUTSIDE PIECE (NOTES 1, 2, 3 AND 4 BELOW)
									ULTIMATE TENSILE STRENGTH OF METAL		
INCHES	D, IN., MIN.	d, IN., MAX.	LB.	CYCLES (60 PER SEC.)	AMPS	IN.	IN.	IN., APPROX.	TENSILE STRENGTH BELOW 70000PSI	TENSILE STRENGTH 70000PSI AND ABOVE	
0.010	3/8	1/8	200	4	4000	3/8	1/4	0.10	130	180	0.010
0.021	3/8	3/16	300	6	6500	7/16	3/8	0.13	320	440	0.021
0.031	3/8	3/16	400	8	8000	7/16	1/2	0.16	570	800	0.031
0.040	1/2	1/4	500	10	9500	1/2	3/4	0.19	920	1200	0.040
0.050	1/2	1/4	650	12	10500	9/16	7/8	0.22	1350	— —	0.050
0.062	1/2	1/4	800	14	12000	5/8	1	0.25	1850	— —	0.062
0.078	5/8	5/16	1100	17	14000	11/16	1 1/4	0.29	2700	— —	0.078
0.094	5/8	5/16	1300	20	15500	3/4	1 1/2	0.31	3450	— —	0.094
0.109	5/8	3/8	1600	23	17500	13/16	1 5/8	0.32	4150	— —	0.109
0.125	7/8	3/8	1800	26	19000	7/8	1 3/4	0.33	5000	— —	0.125

NOTES:

1. TYPE OF STEEL – SAE 1010
2. MATERIAL SHOULD BE FREE FROM SCALE, OXIDES, PAINT, GREASE AND OIL
3. WELDING CONDITIONS DETERMINED BY THICKNESS OF THINNEST OUTSIDE PIECE "T"
4. DATA FOR TOTAL THICKNESS OF PILE-UP NOT EXCEEDING 4 "T". MAXIMUM RATIO BETWEEN TWO THICKNESSES 3 TO 1
5. ELECTRODE MATERIAL, CLASS 2
   MINIMUM CONDUCTIVITY – 75 % OF COPPER
   MINIMUM HARDNESS – 75 ROCKWELL "B"
6. MINIMUM WELD SPACING IS THAT SPACING FOR TWO PIECES FOR WHICH NO SPECIAL PRECAUTIONS NEED BE TAKEN TO COMPENSATE FOR SHUNTED CURRENT EFFECT OF ADJACENT WELDS. FOR THREE PIECES INCREASE SPACING 30 PER CENT.

Table 2—Recommended Practices for Spot-Welding Stainless Steels

THICKNESS "T" OF THINNEST OUTSIDE PIECE (SEE NOTES 1,2,3 AND 4 BELOW)	ELECTRODE DIAMETER AND SHAPE (SEE NOTES) 		NET ELECTRODE FORCE	WELD TIME (SINGLE IMPULSE)	MINIMUM SHEAR STRENGTH LB. ULTIMATE TENSILE STRENGTH OF METAL			WELDING CURRENT (APPROX.) AMPS.		DIAMETER OF FUSED ZONE 	MINIMUM WELD SPACING (SEE NOTE 6 BELOW)	MINIMUM CONTACTING OVERLAP 
INCHES	D, IN., MIN.	d, IN., MAX.	LB.	CYCLES (60 PER SEC.)	70000 UP TO 90000 PSI	90000 UP TO 150000 PSI	150000 PSI AND HIGHER	TENSILE STRENGTH BELOW 150000 PSI	TENSILE STRENGTH 150000 PSI AND HIGHER	IN., APPROX.	℄ TO ℄ IN.	IN.
0.008	3/16	3/32	180	2	60	70	85	2000	2000	0.045	3/16	3/16
0.008	3/16	3/32	200	3	100	130	145	2000	2000	0.055	3/16	3/16
0.010	3/16	1/8	230	3	150	170	210	2000	2000	0.065	3/16	3/16
0.012	1/4	1/8	260	3	185	210	250	2100	2000	0.076	1/4	1/4
0.014	1/4	1/8	300	4	240	250	320	2500	2200	0.082	1/4	1/4
0.016	1/4	1/8	330	4	280	300	380	3000	2500	0.088	5/16	1/4
0.018	1/4	1/8	380	4	320	360	470	3500	2800	0.093	5/16	1/4
0.021	1/4	5/32	400	4	370	470	500	4000	3200	0.100	5/16	5/16
0.025	3/8	5/32	520	5	500	600	680	5000	4100	0.120	7/16	3/8
0.031	3/8	3/16	650	5	680	800	930	6000	4800	0.130	1/2	3/8
0.034	3/8	3/16	750	6	800	920	1100	7000	5500	0.150	9/16	7/16
0.040	3/8	3/16	900	6	1000	1270	1400	7800	6300	0.160	5/8	7/16
0.044	3/8	3/16	1000	8	1200	1450	1700	8700	7000	0.180	11/16	7/16
0.050	1/2	1/4	1200	8	1450	1700	2000	9500	7500	0.190	3/4	1/2
0.056	1/2	1/4	1350	10	1700	2000	2450	10300	8300	0.210	7/8	9/16
0.062	1/2	1/4	1500	10	1950	2400	2900	11000	9000	0.220	1	5/8
0.070	5/8	1/4	1700	12	2400	2800	3550	12300	10000	0.250	1 1/8	5/8
0.078	5/8	5/16	1900	14	2700	3400	4000	14000	11000	0.275	1 1/4	11/16
0.094	5/8	5/16	2400	16	3550	4200	5300	15700	12700	0.285	1 3/8	3/4
0.109	3/4	3/8	2800	18	4200	5000	6400	17700	14000	0.290	1 1/2	13/16
0.125	3/4	3/8	3300	20	5000	6000	7600	18000	15500	0.300	2	7/8

NOTES:

1. TYPES OF STEEL— 301, 302, 303, 304, 308, 309, 310, 316, 317, 321, 347 AND 349
2. MATERIAL SHOULD BE FREE FROM SCALE, OXIDES, PAINT, GREASE AND OIL
3. WELDING CONDITIONS DETERMINED BY THICKNESS OF THINNEST OUTSIDE PIECE "T"
4. DATA FOR TOTAL THICKNESS OF PILE-UP NOT EXCEEDING 4 "T". MAXIMUM RATIO BETWEEN TWO THICKNESSES 3 TO 1
5. ELECTRODE MATERIAL, CLASS 2, CLASS 3 OR CLASS 11

	CLASS 2	CLASS 3	CLASS 11
MINIMUM CONDUCTIVITY —	75%	45%	30% OF COPPER
MINIMUM HARDNESS —	75	95	98 ROCKWELL "B"

6. MINIMUM WELD SPACING IS THAT SPACING FOR TWO PIECES FOR WHICH NO SPECIAL PRECAUTIONS NEED BE TAKEN TO COMPENSATE FOR SHUNTED CURRENT EFFECT OF ADJACENT WELDS. FOR THREE PIECES INCREASE SPACING 30 PER CENT

Table 3—Recommended Practices for Spot Welding Low-Alloy and Medium-Carbon Steels

MATERIAL (SEE NOTES 1, 2, 3 AND 4)			ELECTRODE DIAMETER AND SHAPE			NET ELECTRODE WELD AND TEMPER FORCE	WELD TIME	QUENCH TIME	TEMPER TIME	WELDING CURRENT (APPROX.)	TEMPER CURRENT	MINIMUM CONTACTING OVERLAP	MINIMUM WELD SPACING (SEE NOTE 5 BELOW)	DIAMETER OF FUSED ZONE	MINIMUM WELD STRENGTH		RATIO TENSILE SHEAR STRENGTH
TYPE	CONDITION	"T" THICKNESS INCHES	D INCHES MIN.	d INCHES	R INCHES	LB.	CYCLES (60 PER SEC.)	CYCLES (60 PER SEC.)	CYCLES (60 PER SEC.)	AMPS	% OF WELDING CURRENT	IN.	IN.	INCHES (APPROX.)	SHEAR STRENGTH LBS.	TENSILE STRENGTH LBS.	PERCENT
SAE 1020	HOT ROLLED	0.040	5/8	1/4	6	1475	6	17	6	16000	90	1/2	1	0.23	1360	920	68
SAE 1035	HOT ROLLED	0.040	5/8	1/4	6	1475	6	20	6	14200	91	1/2	1	0.22	1560	520	33
SAE 1045	HOT ROLLED	0.040	5/8	1/4	6	1475	6	24	6	13800	88	1/2	1	0.21	2000	680	33
SAE X-4130	HOT ROLLED	0.040	5/8	1/4	6	1475	6	18	6	13000	90	1/2	1	0.22	2120	640	30
SAE 4340	NORMALIZED & DRAWN	0.031	5/8	3/16	6	900	4	12	4	8250	84	7/16	3/4	0.16	1084	290	27
SAE 4340	NORMALIZED & DRAWN	0.062	3/4	5/16	6	2000	10	45	10	13900	77	5/8	1 1/2	0.27	3840	1440	37
SAE 4340	NORMALIZED & DRAWN	0.125	1	5/8	10	5500	45	240	90	21600	88	7/8	2 1/2	0.55	13680	4000	29
NE 8630	NORMALIZED & DRAWN	0.031	1/2	3/16	6	800	4	12	4	8650	88	7/16	3/4	0.16	1220	524	43
NE 8630	NORMALIZED & DRAWN	0.062	5/8	5/16	6	1800	10	36	10	12800	83	5/8	1 1/2	0.27	4240	2200	52
NE 8630	NORMALIZED & DRAWN	0.125	1	5/8	10	4500	45	210	90	21800	84	7/8	2 1/2	0.55	13200	4500	34
NE 8715	NORMALIZED & DRAWN	0.018	1/2	1/8	6	350	3	4	3	3900	85	7/16	5/8	0.10	400	200	50
NE 8715	NORMALIZED & DRAWN	0.062	5/8	5/16	6	1600	10	28	10	12250	85	5/8	1 1/2	0.27	3300	1800	55
NE 8715	NORMALIZED & DRAWN	0.125	1	5/8	10	4500	45	180	90	22700	85	7/8	2 1/2	0.55	12760	4500	35
NAX 9115	ANNEALED	0.040	5/8	1/4	6	1000	6	14	5	12000	79	1/2	1	0.22	1640	1020	61
NAX 9115	1/2 HARD	0.040	5/8	1/4	6	1240	6	14	5	12000	79	1/2	1	0.22	2040	1020	50
NAX 9115	ANNEALED	0.070	3/4	11/32	6	2325	8	34	8	22600	67	11/16	1 7/8	0.32	4250	2800	66
NAX 9115	1/2 HARD	0.070	3/4	11/32	6	2800	8	34	8	22600	71	11/16	1 7/8	0.32	5050	2520	50

NOTES:

1. MATERIAL SHOULD BE PICKLED OR OTHERWISE CLEANED TO OBTAIN A SURFACE CONTACT RESISTANCE NOT EXCEEDING 200 MICROHMS.
2. DATA IS FOR TWO PIECES OF EQUAL THICKNESS, EACH OF THICKNESS "T".
3. ELECTRODE MATERIAL: RWMA CLASS 2 MINIMUM ELECTRICAL CONDUCTIVITY – 75% OF COPPER, MINIMUM HARDNESS 75 ROCKWELL B
4. ELECTRODE DIAMETER & SHAPE ARE THE SAME FOR BOTH UPPER AND LOWER ELECTRODES.
5. MINIMUM SPACING IS THAT SPACING FOR WHICH NO SPECIAL PRECAUTIONS NEED BE TAKEN TO COMPENSATE FOR SHUNTED CURRENT EFFECT OF ADJACENT WELDS.

Table 4—Recommended Practices for Spot Welding Magnesium Alloys

MATERIAL				A.C. MACHINE			CONDENSER DISCHARGE MACHINE							MATERIAL	
KIND (SEE NOTES 1, 2 AND 3)	THICKNESS	ELECTRODE DIA. AND TIP RADIUS (SEE NOTES 4, 5 AND 6)		NET ELECTRODE FORCE	WELD TIME	WELDING CURRENT (APPROX.)	NET ELECTRODE FORCE	CAPACITANCE (SEE NOTE 7)	CONDENSER VOLTAGE (SEE NOTE 7)	MINIMUM CONTACTING OVERLAP	MINIMUM WELD SPACING	DIAMETER OF FUSED ZONE (APPROX.)	MIN. SHEAR STR.	THICKNESS (SEE NOTES 1, 2 AND 3)	KIND
ASTM ALLOY	IN.	D IN.	R IN.	LBS.	CYCLES (60/SEC.)	AMPS	LBS.	MFD.	VOLTS	IN.	IN.	IN.	LBS.	IN.	ASTM ALLOY
M1	0.016	1/4	2	300	3	17000	300	360	1800	5/16	1/4	0.08	72	0.016	M1
AZ31	0.016	1/4	2	300	2	16000	650	240	1400	5/16	1/4	0.10	140	0.016	AZ31
M1	0.020	3/8	3	300	3	20000	350	600	2000	5/16	1/4	0.12	96	0.020	M1
AZ31	0.020	3/8	3	350	3	18000	700	240	1600	5/16	1/4	0.14	176	0.020	AZ31
M1	0.025	3/8	3	350	4	24000	400	720	2000	5/16	1/4	0.14	128	0.025	M1
AZ31	0.025	3/8	3	400	3	22000	750	360	1800	5/16	1/4	0.16	216	0.025	AZ31
M1	0.032	3/8	3	400	5	26000	500	840	2000	3/8	5/16	0.16	176	0.032	M1
AZ31	0.032	3/8	3	450	4	24000	850	480	2000	3/8	5/16	0.18	272	0.032	AZ31
M1	0.040	1/2	4	450	6	28000	650	960	2000	7/16	3/8	0.18	224	0.040	M1
AZ31	0.040	1/2	4	500	5	26000	1000	720	2200	7/16	3/8	0.20	344	0.040	AZ31
M1	0.051	1/2	4	500	7	30000	850	1200	2000	1/2	7/16	0.21	296	0.051	M1
AZ31	0.051	1/2	4	550	5	29000	1300	840	2200	1/2	7/16	0.23	432	0.051	AZ31
M1	0.064	1/2	4	550	8	32000	1150	1440	2000	9/16	1/2	0.24	384	0.064	M1
AZ31	0.064	1/2	4	600	6	31000	1650	1080	2200	9/16	1/2	0.27	544	0.064	AZ31
M1	0.072	5/8	5	600	9	33000	1400	1680	2000	9/16	9/16	0.26	432	0.072	M1
AZ31	0.072	5/8	5	650	7	32000	1900	1320	2200	9/16	9/16	0.29	608	0.072	AZ31

MI	0.081	5/8	5	650	10	35000	1650	1800	2000	5/8	5/8	0.28	496	0.081	MI
AZ31	0.081	5/8	5	700	8	33000	2200	1440	2200	5/8	5/8	0.31	688	0.081	AZ31
MI	0.091	5/8	5	700	11	36000	1900	2040	2000	11/16	3/4	0.29	560	0.091	MI
AZ31	0.091	5/8	5	750	9	34000	2550	1560	2200	11/16	3/4	0.32	768	0.091	AZ31
MI	0.102	3/4	6	750	12	38000	2200	2160	2000	3/4	7/8	0.31	632	0.102	MI
AZ31	0.102	3/4	6	800	10	36000	2950	1800	2200	3/4	7/8	0.34	864	0.102	AZ31
MI	0.110	3/4	6	800	13	41000	2500	2400	2200	13/16	7/8	0.33	680	0.110	MI
AZ31	0.110	3/4	6	850	11	39000	3250	2040	2200	13/16	7/8	0.36	928	0.110	AZ31
MI	0.128	3/4	6	950	14	45000	3000	2640	2400	7/8	1	0.35	800	0.128	MI
AZ31	0.128	3/4	6	1000	12	42000	4000	2280	2200	7/8	1	0.38	1080	0.128	AZ31

NOTES:

1. TYPES OF MAGNESIUM ALLOYS:
   (Mg + 1.5 Mn) ASTM-MI, An-M-30, Mo, Mh, 3S-O, 3S-H
   (Mg + 3 Al + 1 Zn) ASTN-AZ31, AN-M-29, FS-1a, FS-1h, C52S-O, C52S-H
2. MATERIAL SHOULD BE CHEMICALLY CLEANED OR OTHERWISE MECHANICALLY CLEANED TO A SURFACE CONTACT RESISTANCE NOT TO EXCEED 50 MICROHMS. FOR ALL MAGNESIUM AND MAGNESIUM ALLOYS, EITHER OILED OR PLAIN, THE FOLLOWING CLEANING PRIOR TO WELDING IS RECOMMENDED:
   a. DEGREASE IN SOLVENT, TRICHLORETHYLENE, OR EMULSION-TYPE CLEANER
   b. CLEAN IN HOT ALKALINE CLEANER BY IMMERSION FOR 5 TO 15 MINS. OR BY ELECTROLYTIC MEANS, FOLLOWED BY THOROUGH RINSING, PREFERABLY SPRAY-RINSE.
   c. CLEAN IN CHROMIC ACID-SULFATE SOLUTION * BY IMMERSING, UNTIL OXIDE LAYER IS REMOVED, USUALLY NOT MORE THAN 3 MINUTES, FOLLOWED BY COLD WATER RINSE AND AIR DRY.

   * SOLUTION: 18% CrO_3 + 0.05% H_2SO_4 OR $NaSO_4$ (70-90°F); CHROMIC ACID - 1.5 POUNDS, CONCENTRATED SULFURIC ACID 0.065 Fl. OZ., WATER TO MAKE 1 GALLON.
3. DATA FOR TWO PIECES OF EQUAL THICKNESS. FOR UNEQUAL THICKNESSES WELDING CONDITIONS DETERMINED BY THICKNESS OF THINNEST PIECE. MAXIMUM RATIO BETWEEN TWO THICKNESSES 2 1/2 TO 1.
4. ELECTRODE MATERIAL: CLASS 1
   MINIMUM CONDUCTIVITY - 80% OF COPPER MINIMUM HARDNESS - 65 ROCKEWELL "B"
5. ELECTRODES WATER-COOLED. DOME-SHAPED TIPS FOR BOTH UPPER AND LOWER ELECTRODES. FLAT TIPS WITH DIAMETERS FROM 3/8 TO 1 1/4 INCHES CAN BE USED ON ONE SIDE OF WORK WHERE SURFACES ARE TO BE ESSENTIALLY FREE FROM MARKS. FLAT TIPS SUITABLE FOR MATERIAL THICKNESSES UP TO 0.064 INCHES WITHOUT APPRECIABLE DISPLACEMENT OF WELD.
6. MAXIMUM NUMBER OF SOUND WELDS OBTAINABLE BETWEEN TIP CLEANING ABOUT 25 ON MI ALLOY AND 100 TO 200 ON AZ 31 ALLOY.
7. CONDENSER DISCHARGE MACHINE SETTINGS BASED ON TURNS RATIO OF 480 : 1

Table 5—Recommended Practices for Spot Welding Annealed Nickel

MATERIAL THICKNESS (SEE NOTE 1)	ELECTRODE DIAMETER (NOTES 2 AND 3 BELOW)		NET ELECTRODE FORCE	WELD TIME	WELDING CURRENT (APPROX.)	MINIMUM CONTACTING OVERLAP	MINIMUM WELD SPACING (SEE NOTE 4 BELOW)	DIAMETER FUSED ZONE	MINIMUM SHEAR STRENGTH	MATERIAL THICKNESS (SEE NOTE 1)
INCHES 0.005 TO:	d, IN., MAX.	D, IN., MIN.	LBS.	CYCLES (60 PER SEC.)	AMPS.	IN.	IN.	IN.	LBS.	INCHES 0.005 TO:
0.005	5/32	5/32	100	3	7,100	1/4	3/8	0.10	30	0.005
0.010	5/32	5/32	100	3	7,400	1/4	7/16	0.10	35	0.010
0.015	5/32	5/32	110	3	7,500	1/4	7/16	0.10	40	0.015
0 021	5/32	5/32	110	3	7,800	1/4	1/2	0.10	45	0.021
0.031	5/32	3/16	110	3	8,000	1/4	1/2	0.10	50	0.031
0.063	5/32	3/16	115	3	8,100	1/4	5/8	0.10	50	0.063
0.093	5/32	3/16	115	3	8,150	1/4	5/8	0.10	50	0.093
0.125	5/32	3/16	115	3	8,200	1/4	5/8	0.10	55	0.125
0.010 TO:										0.010 TO:
0.010	3/16	3/16	130	3	11,800	1/4	3/8	0.12	135	0.010
0.015	5/32	3/16	130	3	11,900	1/4	3/8	0.12	145	0.015
0.021	5/32	3/16	130	3	12,000	1/4	7/16	0.12	130	0.021
0.031	5/32	3/16	130	3	12,200	1/4	7/16	0.12	160	0.031
0.063	5/32	3/16	140	3	12,300	1/4	1/2	0.12	185	0.063
0.094	5/32	3/16	140	3	12,300	1/4	5/8	0.12	190	0.094
0.125	5/32	3/16	150	3	12,500	1/4	5/8	0.12	210	0.125
0.015 TO:										0.015 TO:
0.015	3/16	3/16	250	3	12,300	1/4	7/16	0.12	180	0.015
0.021	3/16	3/16	250	3	12,500	1/4	1/2	0.13	250	0.021
0.031	3/16	3/16	250	3	12,600	1/4	1/2	0.13	280	0.031
0 063	3/16	1/4	260	3	12,800	1/4	9/16	0.13	300	0.063
0.094	3/16	5/8	260	3	13,000	1/4	5/8	0.13	305	0 094
0. 125	3/16	5/8	260	3	13,100	1/4	5/8	0.13	310	0.125
0.021 TO:										0.021 TO:
0.021	5/32	5/32	370	4	7,800	5/16	9/16	0.12	350	0.021
0.031	5/32	5/32	370	4	8,200	5/16	5/8	0.12	370	0.031
0.063	5/32	5/32	370	4	8,600	5/16	5/8	0.12	395	0.063
0.094	5/32	5/8	380	4	8,800	5/16	11/16	0.12	430	0.094
0.125	5/32	5/8	380	4	9,000	5/16	3/4	0.13	450	0.125
0.031 TO:										0.031 TO:
0.031	3/16	3/16	900	4	15,400	3/8	7/8	0.16	760	0.031
0.063	3/16	3/16	900	4	15,200	3/8	7/8	0.17	770	0.063
0.094	3/16	3/16	900	6	13,500	3/8	1	0.18	840	0.094
0.125	3/16	5/8	980	6	14,200	3/8	1	0.18	930	0.125
0.063 TO:										0.063 TO:
0.063	1/4	1/4	1720	6	21,600	5/8	1–1/2	0.25	2400	0.063
0.094	1/4	1/4	1800	8	20,000	5/8	1–5/8	0.25	2550	0.094
0.125	1/4	1/4	1800	10	21,000	5/8	1–3/4	0.25	2650	0.125
0.094 TO:										0.094 TO:
0.094	5/16	5/16	2300	12	26,400	3/4	1–7/8	0.31	3600	0.094
0.125	5/16	5/16	2300	20	25,400	3/4	2	0.31	3780	0.125
0.125 TO:										0.125 TO:
0.125	3/8	3/8	3300	20	31,000	7/8	2–1/4	0.37	5600	0.125

NOTES:

1. MATERIAL SHOULD BE FREE FROM SCALE, OXIDES, PAINT, GREASE AND OIL.
2. ELECTRODE SHAPE MAY BE FLAT RATHER THAN DOMED, IN WHICH CASE THE SHEAR STRENGTHS AND NUGGET DIAMETERS WILL BE HIGHER AND LARGER THAN SHOWN IN THE TABLE.
3. ELECTRODE MATERIALS,

	CLASS 1	OR	CLASS 2
MINIMUM CONDUCTIVITY	80% Cu		75% Cu
MINIMUM HARDNESS	68 Rb		75 Rb

4. MINIMUM WELD SPACING IS THAT SPACING FOR TWO PIECES FOR WHICH NO SPECIAL PRECAUTIONS NEED BE TAKEN TO COMPENSATE FOR SHUNTED CURRENT EFFECT OF ADJACENT WELDS. FOR THREE PIECES INCREASE SPACING 30 PERCENT.

Table 6—Recommended Practices for Spot Welding Annealed Monel

MATERIAL THICKNESS (SEE NOTE 1)	ELECTRODE DIAMETER (NOTES 2 AND 3 BELOW)		NET ELECTRODE FORCE	WELD TIME	WELDING CURRENT (APPROX.)	MINIMUM CONTACTING OVERLAP	MINIMUM WELD SPACING (SEE NOTE 4 BELOW)	DIAMETER FUSED ZONE	MINIMUM SHEAR STRENGTH	MATERIAL THICKNESS (SEE NOTE 1)
INCHES	d, IN.,	D, IN.,		CYCLES (60 PER						INCHES
0.005 TO:	MAX	MIN	LBS	SEC.)	AMPS	IN	IN	IN	LBS	0.005 TO:
0.005	5/32	5/32	220	2	5,000	1/4	1/4	0.10	55	0.005
0.010	5/32	5/32	220	2	6,100	1/4	1/4	0.10	60	0.010
0.015	5/32	5/32	[illegible]	2	7,000	1/4	5/16	0.10	75	0.015
0.021	5/32	1/4	220	3	7,200	1/4	3/8	0.11	85	0.021
0.031	5/32	1/4	250	4	7,400	1/4	3/8	0.11	95	0.031
0.063	5/32	5/8	250	4	8,000	1/4	7/16	0.11	90	0.063
0.094	5/32	5/8	250	4	8,600	1/4	1/2	0.11	90	0 094
0 125	5/32	5/8	250	4	8,700	1/4	1/2	0 11	85	0.125
0.010 TO.										0.010 TO
0 010	5/32	5/32	270	2	7,200	1/4	1/4	0.12	145	0.010
0.015	5/32	5/32	280	2	8,600	1/4	5/16	0.12	155	0.015
0.021	5/32	5/32	280	3	8,200	1/4	5/16	0.13	170	0.021
0.031	5/32	5/32	300	4	8,800	1/4	3/8	0.13	190	0.031
0.063	5/32	5/16	300	4	9,200	1/4	7/16	0.13	190	0.063
0.094	5/32	5/8	325	4	9,900	1/4	1/2	0 14	210	0.094
0.125	5/32	5/8	325	4	9,900	1/4	1/2	0.14	220	0.125
0 015 TO:										0.015 TO.
0 015	3/16	3/16	300	2	8,600	1/4	5/16	0 13	250	0 015
0.021	3/16	3/16	300	6	8,200	1/4	3/8	0 13	295	0 021
0 031	3/16	3/16	325	6	9,300	1/4	3/8	0.13	300	0 031
0.063	3/16	5/8	325	6	9,400	1/4	7/16	0.14	350	0 063
0 093	3/16	5/8	325	8	9,500	1/4	1/2	0.14	360	0 093
0.125	3/16	5/8	325	8	9,500	1/4	1/2	0 14	365	0 125
0.021 TO:										0 021 TO.
0.021	3/16	3/16	300	12	6,200	5/16	7/16	0 13	450	0 021
0.031	3/16	3/16	325	12	6,800	5/16	7/16	0 13	460	0 031
0.063	3/16	3/16	325	12	7,200	5/16	1/2	0 14	500	0 063
0 093	3/16	5/8	325	12	7,700	3/8	9/16	0 14	530	0 093
0.125	3/16	5/8	325	12	8,200	3/8	9/16	0.14	550	0 125
0 031 TO:										0.031 TO
0 031	3/16	3/16	700	12	10,500	3/8	5/8	0.17	845	0 031
0.063	3/16	1/4	750	12	11,200	1/2	11/16	0 18	910	0 063
0.094	3/16	5/8	775	12	11,400	1/2	3/4	0 19	1035	0 094
0.125	3/16	5/8	775	12	11,800	1/2	3/4	0 19	1075	0 125
0 063 TO:										0.063 TO:
0.063	5/16	5/16	2700	12	15,300	5/8	1- 1/8	0 31	2060	0.063
0.093	5/16	5/8	2700	12	15,900	5/8	1-3/16	0.31	2180	0 093
0.125	5/16	5/8	2700	12	16,200	5/8	1- 1/4	0 32	2360	0.125
0 093 TO:										0 093 TO.
0.093	3/8	3/8	2760	20	22,600	3/4	1— 1/4	0.37	3080	0.093
0.125	3/8	3/8	2760	20	25,000	3/4	1— 1/4	0 38	4390	0.125
0.125 TO:										0.125 TO:
0.125	1/2	1/2	5000	30	30,000	7/8	1-5/8	0.47	5850	0 125

NOTES

1 MATERIAL SHOULD BE FREE FROM SCALE, OXIDES, PAINT, GREASE AND OIL

2 ELECTRODE SHAPE MAY BE FLAT RATHER THAN DOMED, IN WHICH CASE THE SHEAR STRENGTHS AND NUGGET DIAMETERS WILL BE HIGHER AND LARGER THAN SHOWN IN THE TABLE

3 ELECTRODE MATERIALS,

	CLASS 1	OR CLASS 2
MINIMUM CONDUCTIVITY	80 % Cu	75 % Cu
MINIMUM HARDNESS	68 Rb	75 Rb

4 MINIMUM WELD SPACING IS THAT SPACING FOR TWO PIECES FOR WHICH NO SPECIAL PRECAUTIONS NEED BE TAKEN TO COMPENSATE FOR SHUNTED CURRENT EFFECT OF ADJACENT WELDS
FOR THREE PIECES INCREASE SPACING 30 PERCENT

Table 7—Recommended Practices for Spot Welding Annealed Inconel

MATERIAL THICKNESS (SEE NOTE 1)	ELECTRODE DIAMETER (NOTES 2 AND 3 BELOW)		NET ELECTRODE FORCE	WELD TIME	WELDING CURRENT (APPROX.)	MINIMUM CONTACTING OVERLAP	MINIMUM WELD SPACING (SEE NOTE 4 BELOW)	DIAMETER FUSED ZONE	MINIMUM SHEAR STRENGTH	MATERIAL THICKNESS (SEE NOTE 1)
INCHES	d, IN.,	D, IN.,		CYCLES (60 PER						INCHES
0.005 TO:	MAX	MIN	LBS.	SEC.)	AMPS.	IN.	IN.	IN.	LBS.	0.005 TO:
0.005	5/32	5/32	300	2	7,000	1/4	1/4	0.11	70	0.005
0.010	5/32	3/16	300	4	5,300	1/4	1/4	0.12	100	0.010
0.015	5/32*	3/16	300	4	5,500	1/4	1/4	0.12	105	0.015
0.021	5/32*	3/16	300	6	4,800	1/4	5/16	0.13	110	0.021
0 031	5/32*	3/16	325	6	5,400	1/4	5/16	0.13	120	0.031
0.062	5/32*	5/8	325	6	5,600	1/4	3/8	0.15	135	0.062
0.094	5/32*	5/8	325	6	5,800	1/4	3/8	0.16	145	0.094
0.125	5/32*	5/8	325	6	5,600	1/4	3/8	0.15	130	0.125
0.010 TO:										0.010 TO:
0.010	3/16	3/16	320	4	7,500	1/4	1/4	0.12	175	0.010
0.015	5/32*	3/16	320	4	5,500	1/4	1/4	0.13	215	0.015
0.021	5/32*	3/16	320	6	5,100	1/4	9/32	0.13	215	0.021
0.031	5/32*	3/16	350	6	5,600	1/4	9/32	0.14	290	0.031
0.063	5/32*	3/16	400	6	5,500	1/4	5/16	0.14	315	0.063
0.094	5/32*	5/8	400	6	5,800	1/4	3/8	0.15	350	0.094
0.125	5/32*	5/8	400	6	4,600	1/4	3/8	0.14	370	0.125
0.015 TO:										0.015 TO:
0.015	3/16	3/16	360	6	7,600	1/4	1/4	0.12	295	0.015
0.021	3/16	3/16	360	6	5,400	1/4	1/4	0.12	290	0.021
0.031	5/32*	3/16	400	8	4,600	1/4	9/32	0.13	370	0.031
0.063	5/32*	5/16	400	8	4,700	1/4	5/16	0.13	440	0.063
0.094	3/16*	5/8	400	10	4,700	1/4	11/32	0.16	535	0.094
0.125	3/16	5/8	400	12	4,600	1/4	3/8	0.16	560	0.125
0.021 TO:										0.021 TO:
0.021	5/32	5/32	300	12	4,000	5/16	7/16	0.12	545	0.021
0.031	5/32	3/16	350	12	4,100	5/16	7/16	0.12	535	0.031
0.063	3/16*	5/16	400	12	5,300	5/16	15/32	0.12	580	0.063
0.094	3/16*	5/8	500	12	5,900	5/16	1/2	0.15	670	0.094
0.125	3/16*	5/8	550	12	6,300	5/16	1/2	0.15	690	0.125
0.031 TO:										0.031 TO:
0.031	3/16	3/16	700	12	6,700	3/8	9/16	0.18	920	0.031
0.063	3/16	5/16	700	12	7,100	3/8	5/8	0.18	965	0.063
0.094	1/4*	5/8	700	12	8,300	3/8	11/16	0.20	1250	0.094
0.125	1/4*	5/8	750	12	8,500	3/8	3/4	0.20	1210	0.125
0.063 TO:										0.063 TO:
0.063	5/16	5/16	2070	12	12,000	5/8	1-1/8	0.31	2750	0.063
0.093	5/16	5/8	2450	16	12,000	5/8	1-3/16	0.31	2750	0.093
0.125	5/16	5/8	2600	20	12,000	5/8	1-1/4	0.32	3820	0.125
0.093 TO:										0.093 TO:
0.093	3/8	3/8	3870	20	15,000	3/4	1-3/16	0.37	4400	0.093
0.125	7/16	7/16	5100	30	20,000	3/4	1-1/4	0.40	4700	0.125
0.125 TO:										0.125 TO:
0.125	7/16	7/16	5270	30	20,100	7/8	1-5/16	0.44	6400	0.125

* INDICATES MOLYBDENUM TIPPED ELECTRODE.

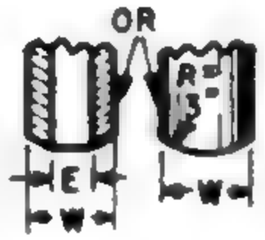
NOTES:

1. MATERIAL SHOULD BE FREE FROM SCALE, OXIDES, PAINT, GREASE AND OIL.
2. ELECTRODE SHAPE MAY BE FLAT RATHER THAN DOMED, IN WHICH CASE THE SHEAR STRENGTHS AND NUGGET DIAMETER WILL BE HIGHER AND LARGER THAN SHOWN IN THE TABLE.
3. ELECTRODE MATERIALS,

	CLASS 1 OR	CLASS 2 OR	MOLYBDENUM FACED
MINIMUM CONDUCTIVITY	80 % Cu	75 % Cu	33 % Cu
MINIMUM HARDNESS	68 Rb	75 Rb	83 Rb

4. MINIMUM WELD SPACING IS THAT SPACING FOR TWO PIECES FOR WHICH NO SPECIAL PRECAUTIONS NEED BE TAKEN TO COMPENSATE FOR SHUNTED CURRENT EFFECT OF ADJACENT WELDS. FOR THREE PIECES INCREASE SPACING 30 PERCENT.

Table 8—Recommended Practices for Seam Welding Low-Carbon Steel

THICKNESS "T" OF THINNEST OUTSIDE PIECE (SEE NOTES 1,2,3 AND 4 BELOW)	ELECTRODE WIDTH AND SHAPE (SEE NOTE 5 BELOW) 		NET ELECTRODE FORCE	ON TIME	OFF TIME (PRESSURE-TIGHT)	WELD SPEED	WELDS PER INCH	WELDING CURRENT (APPROX.)	MINIMUM CONTACTING OVERLAP (SEE NOTE 6 BELOW)	THICKNESS "T" OF THINNEST OUTSIDE PIECE (SEE NOTES 1,2,3 AND 4 BELOW)
INCHES	W, IN., MIN.	E, IN., MAX.	LB.	CYCLES (60 PER SEC.)	CYCLES	IN. PER MIN.		AMPS	IN.	
0.010	3/8	3/16	400	2	1	80	15	8000	3/8	0.010
0.021	3/8	3/16	550	2	2	75	12	11000	7/16	0.021
0.031	1/2	1/4	700	3	2	72	10	13000	1/2	0.031
0.040	1/2	1/4	900	3	3	67	9	15000	1/2	0.040
0.050	1/2	5/16	1050	4	3	65	8	16500	9/16	0.050
0.062	1/2	5/16	1200	4	4	63	7	17500	5/8	0.062
0.078	5/8	3/8	1500	6	5	55	6	19000	11/16	0.078
0.094	5/8	7/16	1700	7	6	50	5.5	20000	3/4	0.094
0.109	3/4	1/2	1950	9	6	48	5	21000	13/16	0.109
0.125	3/4	1/2	2200	11	7	45	4.5	22000	7/8	0.125

NOTES:

1. TYPE OF STEEL — SAE 1010
2. MATERIAL SHOULD BE FREE FROM SCALE, OXIDES, PAINT, GREASE AND OIL
3. WELDING CONDITIONS DETERMINED BY THICKNESS OF THINNEST OUTSIDE PIECE "T"
4. DATA FOR TOTAL THICKNESS OF PILE-UP NOT EXCEEDING 4 "T". MAXIMUM RATIO BETWEEN THICKNESSES 3 TO 1
5. ELECTRODE MATERIAL, CLASS 2
   MINIMUM CONDUCTIVITY — 75% OF COPPER
   MINIMUM HARDNESS — 75 ROCKWELL "B"
6. FOR LARGE ASSEMBLIES MINIMUM CONTACTING OVERLAP INDICATED SHOULD BE INCREASED 30 PER CENT

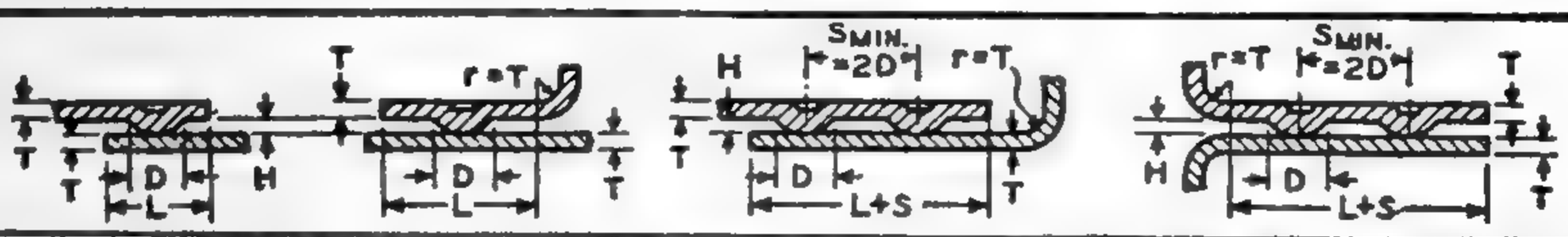
Table 9—Recommended Practices for Seam Welding Stainless Steels

THICKNESS "T" OF THINNEST OUTSIDE PIECE (SEE NOTES 1,2,3 AND 4 BELOW)	ELECTRODE WIDTH AND SHAPE (SEE NOTE 5 BELOW)	NET ELECTRODE FORCE	ON TIME	OFF TIME FOR MAXIMUM SPEED (PRESSURE-TIGHT)		MAXIMUM WELD SPEED		WELDS PER INCH		WELDING CURRENT (APPROX.)	MINIMUM CONTACTING OVERLAP (SEE NOTE 6 BELOW)	THICKNESS "T" OF THINNEST OUTSIDE PIECE (SEE NOTES 1,2,3 AND 4 BELOW)
				CYCLES		IN. PER MINUTE						
INCHES	W, IN., MIN.	LB.	CYCLES (60 PER SEC.)	2"T"	4"T"	2"T"	4"T"	2"T"	4"T"	AMPS.	IN.	INCHES
0.006	3/16	300	2	1	1	60	67	20	18	4000	1/4	0.006
0.008	3/16	350	2	1	2	67	56	18	16	4600	1/4	0.008
0.010	3/16	400	3	2	2	45	51	16	14	5000	1/4	0.010
0.012	1/4	450	3	2	2	48	55	15	13	5600	5/16	0.012
0.014	1/4	500	3	2	3	51	46	14	13	6200	5/16	0.014
0.016	1/4	600	3	2	3	51	50	14	12	6700	5/16	0.016
0.018	1/4	650	3	2	3	55	50	13	12	7300	5/16	0.018
0.021	1/4	700	3	2	3	55	55	13	11	7900	3/8	0.021
0.025	3/8	850	3	3	4	50	47	12	11	9200	7/16	0.025
0.031	3/8	1000	3	3	4	50	47	12	11	10600	7/16	0.031
0.040	3/8	1300	3	4	5	47	45	11	10	13000	1/2	0.040
0.050	1/2	1600	4	4	5	45	44	10	9	14200	5/8	0.050
0.062	1/2	1850	4	5	7	40	41	10	8	15100	5/8	0.062
0.070	5/8	2150	4	5	7	44	41	9	8	15900	11/16	0.070
0.078	5/8	2300	4	6	7	40	41	9	8	16500	11/16	0.078
0.094	5/8	2550	5	6	7	36	38	9	8	16600	3/4	0.094
0.109	3/4	2950	5	7	9	38	37	8	7	16800	13/16	0.109
0.125	3/4	3300	6	6	8	38	37	8	7	17000	7/8	0.125

NOTES:

1. TYPES OF STEEL – 301, 302, 303, 304, 308, 309, 310, 316, 317, 321, 347 AND 349
2. MATERIAL SHOULD BE FREE FROM SCALE, OXIDES, PAINT, GREASE AND OIL
3. WELDING CONDITIONS DETERMINED BY THICKNESS OF THINNEST OUTSIDE PIECE "T"
4. DATA FOR TOTAL THICKNESS OF PILE-UP NOT EXCEEDING 4 "T". MAXIMUM RATIO BETWEEN THICKNESSES 3 TO 1
5. ELECTRODE MATERIAL, CLASS 3
   MINIMUM CONDUCTIVITY – 45% OF COPPER
   MINIMUM HARDNESS – 95 ROCKWELL "B"
6. FOR LARGE ASSEMBLIES MINIMUM CONTACTING OVERLAP INDICATED SHOULD BE INCREASED 30 PER CENT

Table 10—Projection Welding Design Data

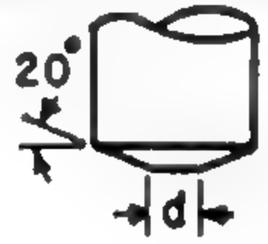


THICKNESS "T" OF THINNEST OUTSIDE PIECE (NOMINAL) (SEE NOTES 1, 2, 3 AND 4 BELOW)	DIAMETER OF PROJECTION "D" (SEE NOTES 7, 8 AND 10 BELOW)	HEIGHT OF PROJECTION "H" (SEE NOTES 7, 9 AND 10 BELOW)	MINIMUM SHEAR STRENGTH (SINGLE PROJECTIONS ONLY) LB.			DIAMETER OF FUSED ZONE MINIMUM (AT WELD INTERFACE)	MINIMUM CONTACTING OVERLAP "L" (SEE NOTES 5 AND 6 BELOW)	THICKNESS "T" OF THINNEST OUTSIDE PIECE (NOMINAL) (SEE NOTES 1, 2, 3 AND 4 BELOW)
			TENSILE STRENGTH BELOW 70,000 PSI	TENSILE STRENGTH 70,000 UP TO 150,000 PSI	TENSILE STRENGTH 150,000 PSI AND ABOVE			
INCHES	IN.	IN.				IN.	IN.	INCHES
0.010	0.055	0.015	130	160	250	0.112	1/8	0.010
0.012	0.055	0.015	170	220	330	0.112	1/8	0.012
0.014	0.055	0.015	200	280	380	0.112	1/8	0.014
0.016	0.067	0.017	240	330	450	0.112	5/32	0.016
0.021	0.067	0.017	320	440	600	0.140	5/32	0.021
0.025	0.081	0.020	450	600	820	0.140	3/16	0.025
0.031	0.094	0.022	635	850	1100	0.169	7/32	0.031
0.034	0.094	0.022	790	1000	1300	0.169	7/32	0.034
0.044	0.119	0.028	920	1300	2000	0.169	9/32	0.044
0.050	0.119	0.028	1350	1700	2400	0.225	9/32	0.050
0.062	0.156	0.035	1950	2250	3400	0.225	3/8	0.062
0.070	0.156	0.035	2300	2800	4200	0.281	3/8	0.070
0.078	0.187	0.041	2700	3200	4800	0.281	7/16	0.078
0.094	0.218	0.048	3450	4000	6100	0.281	1/2	0.094
0.109	0.250	0.054	4150	5000	7000	0.338	5/8	0.109
0.125	0.281	0.060	4800	5700	8000	0.338	11/16	0.125
0.140	0.312	0.066	6000	— —	— —	7/16	3/4	0.140
0.156	0.343	0.072	7500	— —	— —	1/2	13/16	0.156
0.171	0.375	0.078	8500	— —	— —	9/16	7/8	0.171
0.187	0.406	0.085	10000	— —	— —	9/16	15/16	0.187
0.203	0.437	0.091	12000	— —	— —	5/8	1	0.203
0.250	0.531	0.110	15000	— —	— —	11/16	1 1/4	0.250

NOTES:

1. TYPES OF STEEL:
   LOW-CARBON - SAE 1010
   STAINLESS - TYPES 309, 310, 316, 317, 321, 347 AND 349
   (MAX. CARBON CONTENT 0.15%)
2. MATERIAL SHOULD BE FREE FROM SCALE, OXIDES, PAINT, GREASE AND OIL
3. SIZE OF PROJECTION NORMALLY DETERMINED BY THICKNESS OF THINNER PIECE, AND PROJECTION SHOULD BE ON THICKER PIECE WHERE POSSIBLE
4. DATA BASED ON THICKNESS OF THINNER SHEET, AND FOR TWO THICKNESSES ONLY
5. CONTACTING OVERLAP DOES NOT INCLUDE ANY RADII FROM FORMING, ETC.
6. WELD SHOULD BE LOCATED IN CENTER OF OVERLAP
7. PROJECTION SHOULD BE MADE ON PIECE OF HIGHER CONDUCTIVITY WHEN DISSIMILAR METALS ARE WELDED
8. FOR DIAMETER OF PROJECTION "D" A TOLERANCE OF ± 0.003 IN. IN MATERIAL UP TO AND INCLUDING 0.050 IN. IN THICKNESS AND ± 0.007 IN. IN MATERIAL OVER 0.050 IN. IN THICKNESS MAY BE ALLOWED
9. FOR HEIGHT OF PROJECTION "H" A TOLERANCE OF ± 0.002 IN. IN MATERIAL UP TO AND INCLUDING 0.050 IN. IN THICKNESS AND ± 0.005 IN. IN MATERIAL OVER 0.050 IN. IN THICKNESS MAY BE ALLOWED
10. SEE TABLE 13 FOR DATA ON PUNCH AND DIE DESIGNS FOR MAKING PROJECTIONS

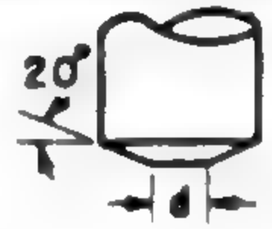
Table 11—Manufacturing Process Data for Projection Welding Mild Steel

THICKNESS "T" OF THINNEST OUTSIDE PIECE (NOMINAL) (SEE NOTES 1, 2 AND 3 BELOW)	ELECTRODE FACE DIAMETER "d" (d = 2 x PROJ. DIA.) (SEE NOTE 4 BELOW) 	NET ELECTRODE FORCE	WELD TIME	HOLD TIME	WELDING CURRENT (AT ELECTRODES) 60 CYCLES A.C. (APPROX.)	THICKNESS "T" OF THINNEST OUTSIDE PIECE (NOMINAL) (SEE NOTES 1, 2 AND 3 BELOW)
INCHES	IN.	LB.	CYCLES (60 PER SEC.)	CYCLES (60 PER SEC.)	AMPS	INCHES
0.014	1/8	175	7	15	5000	0.014
0.021	3/32	300	10	15	6000	0.021
0.031	3/16	400	15	15	7000	0.031
0.044	1/4	400	20	15	7000	0.044
0.062	5/16	700	25	15	9500	0.062
0.078	3/8	1200	30	30	13000	0.078
0.094	7/16	1200	30	30	14500	0.094
0.109	1/2	1700	30	45	16000	0.109
0.125	9/16	1700	30	45	17000	0.125
PROCESS DATA FOR OTHER THICKNESSES SHOWN IN TABLE 10 NOT YET AVAILABLE						

NOTES:

1. TYPES OF STEEL—SAE 1010 (MAX. CARBON CONTENT 0.15%)
2. MATERIAL SHOULD BE FREE FROM SCALE, OXIDES, PAINT, GREASE AND OIL
3. DATA BASED ON THICKNESS OF THINNER SHEET, AND FOR TWO THICKNESSES ONLY. MAXIMUM RATIO BETWEEN TWO THICKNESSES 3 TO 1
4. SEE TABLE 10 FOR STANDARD PROJECTIONS
5. ELECTRODE MATERIAL, CLASS 2
   MINIMUM CONDUCTIVITY - 75% OF COPPER
   MAXIMUM HARDNESS — 75 ROCKWELL "B"

Table 12—Manufacturing Process Data for Projection Welding Stainless Steels

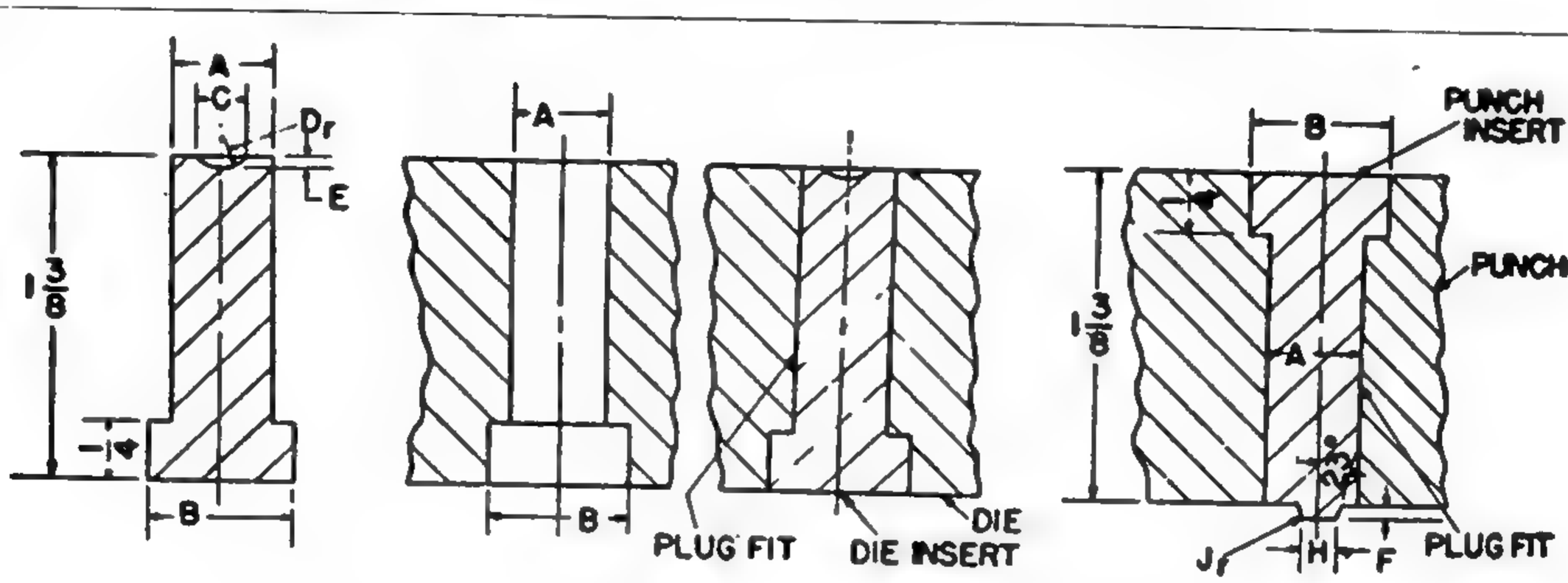
THICKNESS "T" OF THINNEST OUTSIDE PIECE (NOMINAL) (SEE NOTES 1, 2 AND 3 BELOW)	ELECTRODE FACE DIAMETER "d" (d = 2 x PROJ. DIA.) (SEE NOTE 4 BELOW) 	NET ELECTRODE FORCE	WELD TIME	HOLD TIME	WELDING CURRENT (AT ELECTRODES) 60 CYCLES A.C. (APPROX.)	THICKNESS "T" OF THINNEST OUTSIDE PIECE (NOMINAL) (SEE NOTES 1, 2 AND 3 BELOW)
INCHES	IN.	LB.	CYCLES (60 PER SEC.)	CYCLES (60 PER SEC.)	AMPS	INCHES
0.014	1/8	300	7	15	4500	0.014
0.021	3/32	500	10	15	4750	0.021
0.031	3/16	700	15	15	5750	0.031
0.044	1/4	700	20	15	6000	0.044
0.062	5/16	1200	25	15	7500	0.062
0.078	3/8	1900	30	30	10000	0.078
0.094	7/16	1900	30	30	10000	0.094
0.109	1/2	2800	30	45	13000	0.109
0.125	9/16	2800	30	45	14000	0.125
PROCESS DATA FOR OTHER THICKNESSES SHOWN IN TABLE 10 NOT YET AVAILABLE						

NOTES:

1. TYPES OF STEEL – 309, 310, 316, 317, 321, 347 AND 349 (NON-HARDENABLE; MAX. CARBON CONTENT – 0.15%)
2. MATERIAL SHOULD BE FREE FROM SCALE, OXIDES, PAINT, GREASE AND OIL
3. DATA BASED ON THICKNESS OF THINNER SHEET, AND FOR TWO THICKNESSES ONLY. MAXIMUM RATIO BETWEEN TWO THICKNESSES 3 TO 1
4. SEE TABLE 10 FOR STANDARD PROJECTIONS
5. ELECTRODE MATERIAL,

	CLASS 2	OR	CLASS 12
MINIMUM CONDUCTIVITY —	75		29% OF COPPER
MAXIMUM HARDNESS —	75		100 ROCKWELL "B"

Table 13—Projection Welding Punch and Die Design Data



MAT. THICKNESS	PT. NO.	A	B	±.002 C	Dr	±.001 E	±.001 F	±.001 H	Jr
.012 TO.016	1	3/8	9/16	.055	.033	.015	.015	.035	.005
.016 TO.020	2	3/8	9/16	.067	.042	.017	.020	.039	.005
.025	3	3/8	9/16	.081	.050	.020	.025	.044	.005
.031	4	3/8	9/16	.094	.062	.022	.030	.050	.005
.035	5	3/8	9/16	.094	.062	.022	.030	.050	.005
.044	6	3/8	9/16	.119	.078	.028	.035	.062	.005
.050	7	3/8	9/16	.119	.078	.028	.035	.062	.005
.062	8	3/8	9/16	.156	.105	.035	.043	.081	.005
.071	9	3/8	9/16	.156	.105	.035	.043	.081	.005
.078	10	3/8	9/16	.187	.128	.041	.055	.104	.010
.094	11	1/2	11/16	.218	.148	.048	.065	.115	.010
.109	12	1/2	11/16	.250	.172	.054	.075	.137	1/64
.125	13	1/2	11/16	.281	.193	.060	.085	.154	1/64
.140	14	1/2	11/16	.312	.217	.066	.096	.172	1/64
.156	15	5/8	13/16	.343	.243	.072	.107	.191	1/64
.171	16	5/8	13/16	.375	.265	.078	.118	.210	1/64
.187	17	5/8	13/16	.406	.285	.085	.130	.229	1/64
.203	18	11/16	7/8	.437	.308	.091	.143	.240	.020
.250	19	13/16	1	.531	.375	.110	.175	.285	.025

MATERIAL:

MAKE DIE & PUNCH INSERTS FROM AIR-HARDENING CHROME-VANADIUM STEEL. FINISH ALL OVER AND HARDEN TO 65-68 ROCKWELL "C" SCALE.

NOTE:

EACH PART NUMBER REPRESENTS ONE COMPLETE DIE UNIT WHICH IS MADE UP OF PUNCH & DIE INSERT

ALL WORKING SURFACES OF DIE UNIT MUST BE POLISHED.

Table 14—Recommended Practices for Pulsation Welding Low-Carbon Steel

COMBINATION OF THICKNESSES TO BE WELDED (NOTES 1 AND 2 BELOW)		ELECTRODE DIAMETER AND SHAPE (NOTE 3 BELOW)		NET ELECTRODE FORCE	WELD TIME ON 20 CYCLES OFF 5 CYCLES (60 PER SEC.) NO. OF PULSATIONS			WELDING CURRENT (APPROX.)	MINIMUM CONTACTING OVERLAP	MINIMUM DIAMETER OF FUSED ZONE	MINIMUM SHEAR STRENGTH (FOR STEEL OF TENSILE STRENGTH LESS THAN 70,000 PSI)	COMBINATION OF THICKNESSES TO BE WELDED (NOTES 1 AND 2 BELOW)	
					SINGLE WELDS	ADJACENT WELDS							
T-1	T-2	D, IN., MIN.	d, IN., MAX.	LB.		1 IN. TO 2 IN. CENTERS	2 IN. TO 4 IN. CENTERS	AMPS	IN.	IN. APPROX.	LB.	T-1	T-2
1/8	1/8	1	7/16	1800	3	5	4	18000	7/8	3/8	5000	1/8	1/8
1/8	3/16	1	7/16	1800	3	5	4	18000	7/8	3/8	5000	1/8	3/16
1/8	1/4	1	7/16	1800	3	5	4	18000	7/8	3/8	5000	1/8	1/4
3/16	3/16	1 1/4	1/2	1950	6	20	14	19500	1 1/8	9/16	10 000	3/16	3/16
3/16	1/4	1 1/4	1/2	1950	6	20	14	19500	1 1/8	9/16	10000	3/16	1/4
3/16	5/16	1 1/4	1/2	1950	6	20	14	19500	1 1/8	9/16	10000	3/16	5/16
1/4	1/4	1 1/4	9/16	2150	12	24	18	21500	1 3/8	3/4	15000	1/4	1/4
1/4	5/16	1 1/4	9/16	2150	12	24	18	21500	1 3/8	3/4	15000	1/4	5/16
5/16	5/16	1 1/2	5/8	2400	15	30	23	24000	1 1/2	7/8	20000	5/16	5/16

NOTES :

1. TYPE OF STEEL — SAE 1010
2. MATERIAL SHOULD BE FREE FROM SCALE, OXIDE, PAINT, GREASE AND OIL
3. ELECTRODE MATERIAL, CLASS 2
   MINIMUM CONDUCTIVITY — 75 % OF COPPER
   MINIMUM HARDNESS — 75 ROCKWELL "B"

Table 15—Recommended Practices for Pulsation Welding Stainless Steels

THICKNESS "T" OF THINNEST OUTSIDE PIECE (SEE NOTES 1,2,3 AND 4 BELOW)	ELECTRODE DIAMETER AND SHAPE (SEE NOTE 5 BELOW)		NET ELECTRODE FORCE	WELD TIME ON 15 CYCLES OFF 6 CYCLES (60 PER SEC.)	WELDING CURRENT (APPROX.) AMPS		MINIMUM CONTACTING OVERLAP	MINIMUM WELD SPACING (SEE NOTE 6 BELOW)	MINIMUM DIAMETER OF FUSED ZONE	MINIMUM SHEAR STRENGTH LB.		THICKNESS "T" OF THINNEST OUTSIDE PIECE (SEE NOTES 1,2,3 AND 4 BELOW)
					BASE METAL TENSILE STRENGTH					ULTIMATE TENSILE STRENGTH OF METAL		
INCHES	D, IN., MIN.	d, IN., MAX.	LB.	NO. OF PULSATIONS	BELOW 150000 PSI	150000PSI AND HIGHER	IN.	IN.	IN.	90000 UP TO 150000 PSI	150000 PSI AND HIGHER	INCHES
0.156	1	1/2	4000	4	20700	17500	1 1/4	1 7/8	0.440	7600	10000	0.156
0.187	1	1/2	5000	5	21500	18500	1 1/2	2	0.500	9750	12300	0.187
0.203	1	5/8	5500	6	22000	19000	1 5/8	2 1/8	0.530	10600	13000	0.203
0.250	1	5/8	7000	7	22500	20000	1 3/4	2 3/8	0.600	13500	17000	0.250

NOTES:

1. TYPES OF STEEL – 301, 302, 303, 304, 308, 309, 310, 316, 317, 321, 347 AND 349
2. MATERIAL SHOULD BE FREE FROM SCALE, OXIDES, PAINT, GREASE AND OIL
3. WELDING CONDITIONS DETERMINED BY THICKNESS OF THINNEST OUTSIDE PIECE "T"
4. DATA FOR TOTAL THICKNESS OF PILE-UP NOT EXCEEDING 4 "T". MAXIMUM RATIO BETWEEN TWO THICKNESSES 3 TO 1
5. ELECTRODE MATERIAL,

	CLASS 3	OR	CLASS II
MINIMUM CONDUCTIVITY –	45%		30% OF COPPER
MINIMUM HARDNESS –	95		98 ROCKWELL "B"

6. MINIMUM WELD SPACING IS THAT SPACING FOR TWO PIECES WHICH NO SPECIAL PRECAUTIONS NEED BE TAKEN TO COMPENSATE FOR SHUNTED CURRENT EFFECT OF ADJACENT WELDS. FOR THREE PIECES INCREASE SPACING 30 PER CENT

BIBLIOGRAPHY

1. *Measurement of the Spot-Welding Machine Variables,* G. S. Bernard, The Welding Journal, March 1938.

2. *Resistance Welding Electrodes,* R. H. Harrington, The Welding Journal Res. Suppl., October 1938.

3. *Spot Welding of Low-Carbon and Stainless Steels,* W. F. Hess and R. L. Ringer, Jr., The Welding Journal Res. Suppl., October 1938.

4. *Data on Spot Welding Low-Carbon Steel,* W. F. Hess and R. L. Ringer, Jr., The Welding Journal Res. Suppl., February 1939.

5. *Spot Welding 18-8 Stainless Steel to Yellow Brass,* F. R. Hensel, E. J. Larsen and E. F. Holt, The Welding Journal, March 1939.

6. *Contact Resistance in Spot Welding,* F. J. Studer, The Welding Journal Res. Suppl., June 1939.

7. *Spot Welding of Low-Carbon and Stainless Steels,* W. F. Hess and R. A. Wyant, The Welding Journal Res. Suppl., June 1939.

8. *Strength of Welds,* E. Warnent, L. Vandapere, A. Koukoff and P. Lucas, The Welding Journal Res. Suppl., July 1939.

9. *Spot, Flash and Resistance Welding Fundamentals,* D. E. Babcock, The Welding Journal, August 1939.

10. *Fundamentals of Resistance Welding,* S. M. Humphrey, The Welding Journal, Feburary 1940.

11. *Resistance Welding Current Measurements,* E. W. Clark, The Welding Journal, March 1940.

12. *The Application of Projection Welding,* L. H. Frost, The Welding Journal, March 1940.

13. *Changes in the Shape of Spherical Spot-Welding Electrodes,* W. F. Hess and R. A. Wyant, The Welding Journal Res. Suppl., October 1940.

14. *Fundamentals of Resistance Welding,* R. S. Pelton, The Welding Journal Res. Suppl., October 1940.

15. *Recorders and Indicators for Resistance Welding Machines,* W. C. Hutchins, The Welding Journal, November 1940.

16. *Electro-Magnetic Stirring Action in a Spot Weld,* A. M. Unger, The Welding Journal, January 1941.

17. *Structural Spot Welding—Consistency Control Methods,* A. M. Unger, The Welding Journal, October 1941.

18. *Resistance Welding Zinc-Alloy Die Castings,* R. T. Gillette, The Welding Journal, January 1941.

19. *Spot Welding Galvanized and Corrosion Resisting Steel Smoke Pipes,* H. O. Klinke, The Welding Journal, October 1941.

20. *Thermal Gradients in Spot Welding Electrodes,* F. R. Hensel, E. J. Larsen and E. F. Holt, The Welding Journal, December 1941.

21. *Spot Welding—Part III, Contact Resistance,* R. F. Tylecote, The Welding Journal Res. Suppl., December 1941.

22. *Behavior of Spot Welds Under Impact,* A. M. Unger, H. A. Matis and E. P. Gruca, The Welding Journal Res. Suppl., February 1942.

23. *Device for Measuring Tip Force and Current in Spot Welding,* H. Wolfe and R. W. Powell, The Welding Journal Res. Suppl., June 1942.

24. *The Spot Welding of N.A.X. High-Tensile Steel,* C. R. Schroder, The Welding Journal, October 1942.

25. *The Spot Welding of 0.040-In. SAE X-4130 Steel,* W. F. Hess and D. C. Herrschaft, The Welding Journal Res. Suppl., October 1942

26. *The Effect of Weld Spacing on the Strength of Spot-Welding Joints,* R. Della-Vedowa and M. M. Rockwell, The Welding Journal Res. Suppl., October 1942.

27. *The Spotweldability of Low-Carbon and Aircraft Steels,* L. C. Bibber and J. Heuschkel, The Welding Journal Res. Suppl., December 1942.

28. *Refrigerant-Cooled Spot-Welding Electrodes,* W. G. Moehlenpah, The Welding Journal Res. Suppl., April 1943.

29. *Resistance Welding Below the Frost Line,* A. L. Munson, The Welding Journal, May 1943.

30. *Electric Resistance-Welded Steel Tubing—Its Quality Control and Application,* R. D. Malm, The Welding Journal, October 1943.

31. *A Study of the Application of Refrigeration to the Cooling of Spot Welding Electrodes,* W. F. Hess, R. A. Wyant, O. E. Stabler and F. J. Winsor, The Welding Journal Res. Suppl., November 1943.

32. *Resistance Welding Data Book,* P. R. Mallory Co., Third Edition, 1944.

33. *Better Welds Through Regulated Welding Current,* B. Cooper, The Welding Journal, January 1944.

34. *Quality Control in Aircraft Spot Welding,* N. C. Clark, The Welding Journal, January 1944.

35. *Dual Pressure Systems as Applied to Resistance Welding Machines,* S. M. Humphrey, The Welding Journal, February 1944.

36. *Production Spot Weld Testing,* Capt. J. K. Dawson, The Welding Journal, February 1944.

37. *Spot-Weld Joint Efficiency,* S. Wong and C. W. Steward, The Welding Journal Res. Suppl., April 1944.

38. *The Geometry of a Spot-Welding Tip and Its Relation to Tip Life,* E. D. Crawford and C. W. Steward, The Welding Journal Res. Suppl., October 1944.

39. *The Spot-Welding Properties of Rust-Proofed Mild Steel Sheet,* W. S. Simmie and A. J. Hipperson, The Welding Journal Res. Suppl., August 1944.

40. *Spot Welding High Tensile Steels with Automatic Post-Heat Treatment,* W. S. Simmie and A. J. Hipperson, The Welding Journal Res. Suppl., March 1945.

41. *Determination by Statistical Analysis of Process Minimums for Spot Welding,* Harold Robinson, The Welding Journal, May 1945.

42. *An Analysis and Comparison of Various Resistance Welding Systems,* R. L. Longini, The Welding Journal, June 1945.

43. *Resistance Welding Fundamentals,* F. R. Woodward, The Welding Journal, August 1945.

44. *Resistance Welding Laboratories and Their Instruments,* R. T. Gillette, The Welding Journal, September 1945.

45. *Some Conclusions Regarding Resistance Welding and Statistical Quality Control,* J. B. Butler, The Welding Journal, October 1945.

46. *Instrumentation of the Spot Welder and Investigation of the Spot Welding of 0.091-0.091 In. 24ST Alclad Sheet,* R. C. McMaster and N. A. Begovia, The Welding Journal Res. Suppl., October 1945.

47. *Resistance Welding Manual,* Resistance Welder Manufacturers' Association, 1946.

48. *Method for Welding Sheet Aluminum to SAE 4140 Steel,* W. F. Hess and E. F. Nippes, Jr., The Welding Journal Res. Suppl., March 1946.

49. *Variation in Quality of Spot Welds in Low-Carbon Steel Over a Range of Welding*

Variables, J. J. Riley, The Welding Journal, September 1946.

50. *Causes and Prevention of Defects in Welding,* F. S. Dever, The Welding Journal, September 1946.

51. *Progress Report on the Spot Welding of High-Tensile Carbon and Low-Alloy Steels,* W. F. Hess, W. D. Doty and W. J. Childs, The Welding Journal Res. Suppl., September 1946.

52. *The Selection of Spot-Welding Schedules for Low-Carbon Steel,* J. Heuschkel, The Welding Journal Res. Suppl., October 1946.

53. *A Summary of Spot Welding of High-Tensile Carbon and Low Alloy Steels,* W. D. Doty and W. J. Childs, The Welding Journal Res. Suppl., October 1946.

54. *A Preliminary Investigation of the Spot Welding of Scaly and Rusty Structural Steel,* W. D. Doty and W. J. Childs, The Welding Journal Res. Suppl., June 1947.

55. *Shunt Circuit Impedance in Spot Welding 1/8, 1/4 and 1/2 Mild Steel,* R. H. Blair, The Welding Journal, October 1947.

56. *Some Metallurgical Aspects of Carbon Steel Spot Welding,* J. Heuschkel, The Welding Journal Res. Suppl., October 1947.

57. *The Fundamentals of Spot Welding Steel Plate,* W. F. Hess, W. D. Doty and W. J. Childs, The Welding Journal Res. Suppl., October 1947.

58. *The Heat Treatment of Spot Welds in Steel Plate,* W. F. Hess, W. D. Doty and W. J. Childs, The Welding Journal Res. Suppl., November 1947.

59. *A Study of Projection Welding,* W. F. Hess and W. J. Childs, The Welding Journal Res. Suppl., December 1947.

60. *Recommended Practices for Resistance Welding,* American Welding Society, 1950.

CHAPTER 17

FLASH, UPSET AND PERCUSSION WELDING*

A. FLASH WELDING

FUNDAMENTALS OF PROCESS

Definition and General Descriptions

FLASH WELDING is a resistance-welding process wherein coalescence is produced, simultaneously over the entire area of abutting surfaces, by the heat obtained from resistance to the flow of electric current between the two surfaces, and by the application of pressure after heating is substantially completed. Flashing and upsetting are accompanied by expulsion of metal from the joint.

Principles of Operation

Sequence.—In many applications, there are other steps involved in the cycle than those referred to above. The following list indicates the sequence of operations that may be required.

*1. Load machine.
*2. Clamp work.
*3. Apply welding voltage.
4. Apply preheating pressure.
5. Preheat.
6. Release pressure.
*7. Contact parts lightly for flashing.
8. Flash at high voltage.
*9. Flash at normal voltage.
*10. Upset.
11. Postheat.
*12. Cut off welding current.
*13. Unclamp work.
*14. Return platen and unload.
15. Trim flash.

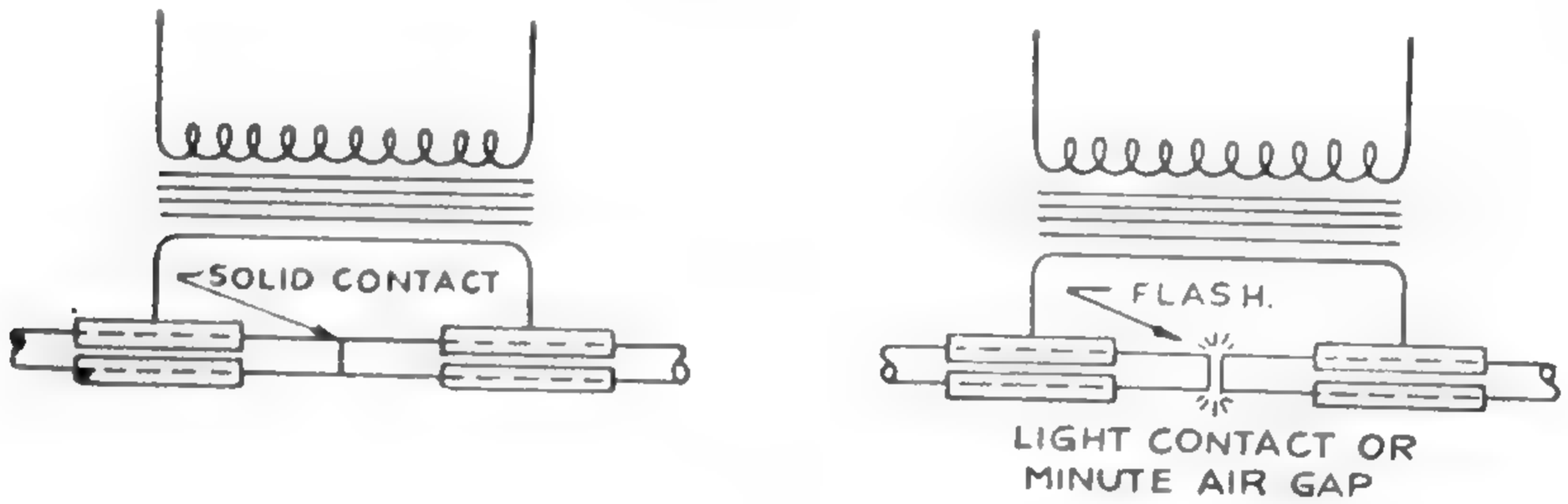


Fig. 1.—Relationship of Parts for Flash Welding

Basically flash welding consists of placing two pieces of metal in an electric circuit adjacent to each other, in very light contact, and applying an electric potential that causes a current of sufficient magnitude to flow through the circuit to form a *flashing* action between the adjacent pieces of metal, thereby heating them to the fusion point with the weld being consummated by the application of sufficient pressure. Figure 1 shows the relationship of parts for this application.

By using only the operations indicated with an asterisk(*), the basic or most generally used cycle is obtained. These operations illustrate a flash welding cycle in one of its more complicated forms. All of the steps are necessary for certain applications. The additional operations are used only when they become necessary because of the nature of the material being welded, or due to the design of the parts. The basic cycle is followed in all

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cases except in the trimming of the flash, which may or may not be necessary according to the requirements of the particular assembly.

When welding tubes, it is often impossible to remove the flash from the inside, and in certain designs, wherein neither interference nor physical requirements demand that the flash be removed, the parts are left as welded. The use of preheating and postheating periods is discussed later in this chapter.

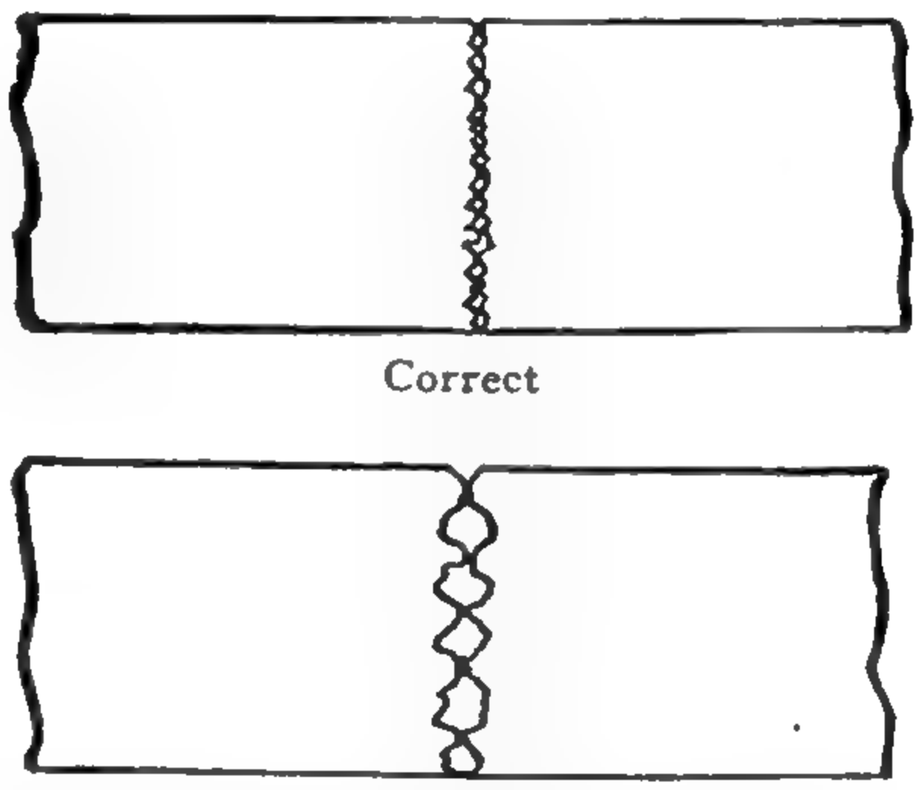
When flash welding heavy sections, it is often difficult to establish a flashing action due to the fact that rather large amounts of cold metal are present at the flashing surfaces. Preheating of the parts prior to flashing is sometimes used to improve this condition. Another method is to bevel the surfaces to be welded. It is also possible to establish the flashing action manually by intermittently shorting the pieces until sufficient temperature is obtained so that flashing may take place as a part of the automatic cycle of the machine. Item 8 in the Sequence of Operations indicates another method of establishing a flashing action wherein a higher open-circuit voltage is used at the start of flashing than is used later in the cycle. All of the foregoing methods have been proved to be satisfactory in production and in many instances combinations of them are employed.

Flashing.—A brief description has been given of the flashing action which takes place between the two parts prior to upset. It is necessary that the platen be accelerated at the proper rate to maintain a continuous flashing action. This rate is more or less determined by the size of the parts being welded, as well as by the amount of electrical energy being used. Both the instantaneous and the average rates of flashing must be considered.

The average rate of flashing may be understood as the total distance the platen travels during the flashing period divided by the time required for this travel. If the rate is too low, flashing is only obtained intermittently and it is difficult to obtain sufficient heat in the parts to provide for an adequate upset. Should the rate be too high, it is entirely possible that the pieces may only freeze together prior to upset, without making a proper weld.

The overall flashing time may be considered as the full amount of time during which the flashing action takes place. If the time is too short, insufficient heat is generated in the parts and it is impossible to obtain the proper upset. In contrast, if it is too long, the welding surfaces are overheated and it is also impossible to obtain a proper upset. This is due to the fact that there is a rather large amount of molten or plastic material to be forced out of the weld area, making it difficult to utilize the correct pressure during the upset cycle.

On automatic machines the flashing rate and the flashing time may usually be considered as a single variable once the cam is designed, inasmuch as any change in cam speed affects both variables.



Correct

Incorrect

Fig. 2.—Effect of Correct Rate of Energy Input Compared with Too High Rate of Input

Flashing current and voltage are usually determined by the transformer setting and, therefore, cannot be individually changed. A setting on a high tap on the transformer tends to increase both the current and voltage, whereas a low tap setting decreases them. The effect of having too low an energy input is similar to that of having too high a rate of flashing, in that it is difficult to obtain sufficient heat and there is a possibility of freezing the pieces together as the platen is accelerated. Too high a rate of energy input tends to separate the work pieces during flashing, which in turn creates large craters on the flashing surfaces and makes it difficult to upset to sound material. Figure 2 indicates the effect of flashing with too high a rate of energy input.

In establishing a new welding procedure it may be desirable to flash the parts without upsetting them and then examine the ends to determine whether or not they are suitable for upsetting without danger of pockets or slag which cannot be squeezed out during upset.

In making a flash weld, when initial contact is established there is a series of very light, localized contacts between the two surfaces as indicated in Fig. 3, which result in a high concentration of current at those points. This localization of current heats up the minute areas to incandescence and causes the molten metal to be blown out in the form of small particles. These localized short circuits or *bridges* occur successively over the entire surface at an accelerating rate until such time as the entire surface reaches a fusing temperature.

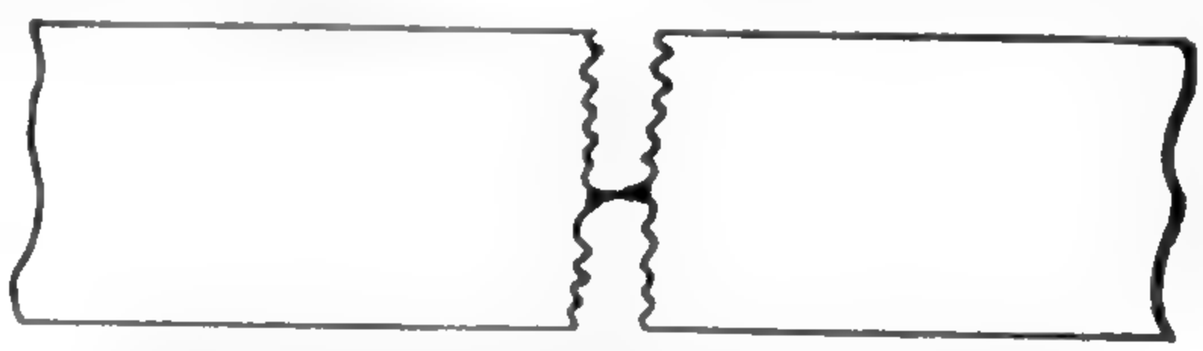


Fig. 3.—Localized Bridging at Initial Contact

As soon as sufficient heat has been generated to obtain a fusing temperature, an upset or forging pressure is applied suddenly and the welding current is cut off. To obtain sufficient plasticity for upsetting some large pieces, it is necessary to prolong the flashing cycle after the surfaces have reached a fusing temperature. Some authorities have maintained that the flashing action assists in providing a protective atmosphere by combustion of particles expelled. It is also believed that combustion of these particles furnishes heat in addition to that obtained from the electrical energy. However, recent investigations indicate that the importance of these effects is negligible.

There have been numerous instances, in recent years, where shielding atmospheres such as city gas, hydrogen and the inert gases have been tried to improve the quality of the weld joint. This practice has not been widespread, but research has been conducted in several laboratories. In several instances production runs of flash-welded assemblies have been accomplished with the aid of a shielding gas. While the results of such procedures to date are not conclusive, the practice might be of benefit when there is need for the utmost in weld quality.

Upsetting.—After the flashing action has progressed for a sufficient time to establish a plastic zone of metal, the upset pressure is applied rapidly to complete the weld. The purpose of this pressure is twofold; first, to provide forging action of sufficient intensity to unite the plastic weld metal and, second, to squeeze out all slag or oxidized materials which may be on the abutting surfaces just prior to upset.

The current flowing through the pieces during upset must be sufficient to prevent the material from chilling too rapidly. If the upset current is too low, it is impossible to squeeze out all of the oxides, slag inclusions, etc. This also will cause an improper upset as was discussed with respect to insufficient heat in the material prior to upset. On the other hand, too high an upset current may blow out molten material adjacent to the weld, causing a defect. It is therefore necessary to have sufficient current to provide a proper upsetting action, but with no blowing out or loss of pressure due to the material becoming plastic back of the weld region. Excessive upset current may also result in overheating to the extent of burning the weld apart.

The upset pressure should extrude the molten metal so that the weld is made in the plastic metal immediately adjacent. This pressure is greatest at the center of the section and decreases toward the outer edges. Since slag which is trapped in the center of the section must travel the farthest, it is reasonable to expect that the center section must be freed first of any unwanted slag particles during upset. If these foreign particles become trapped on their way out, they will produce defects in the completed weld.

Therefore, the upset pressure must be sufficient to completely extrude the molten metal at the weld line beyond the original cross-section of the work-piece, in order to insure that all slag and inclusions will

be removed when the upset material is removed. After removing the flash by machining, there should be no external evidence of the weld. If the weld is sectioned and etched, there should be no evidence of porosity or slag. Such porosity or defects indicate incomplete upset due either to insufficient upset pressure or insufficient plasticity of the metal in the weld region.

with various materials are indicated in the section of this chapter on Recommended Practices. Figure 4 illustrates the appearance of two round shafts before flash welding, after welding, after the flash has been removed and after the flash and upset have been removed.

Effect of Process on Materials Welded

As previously described, flash welding

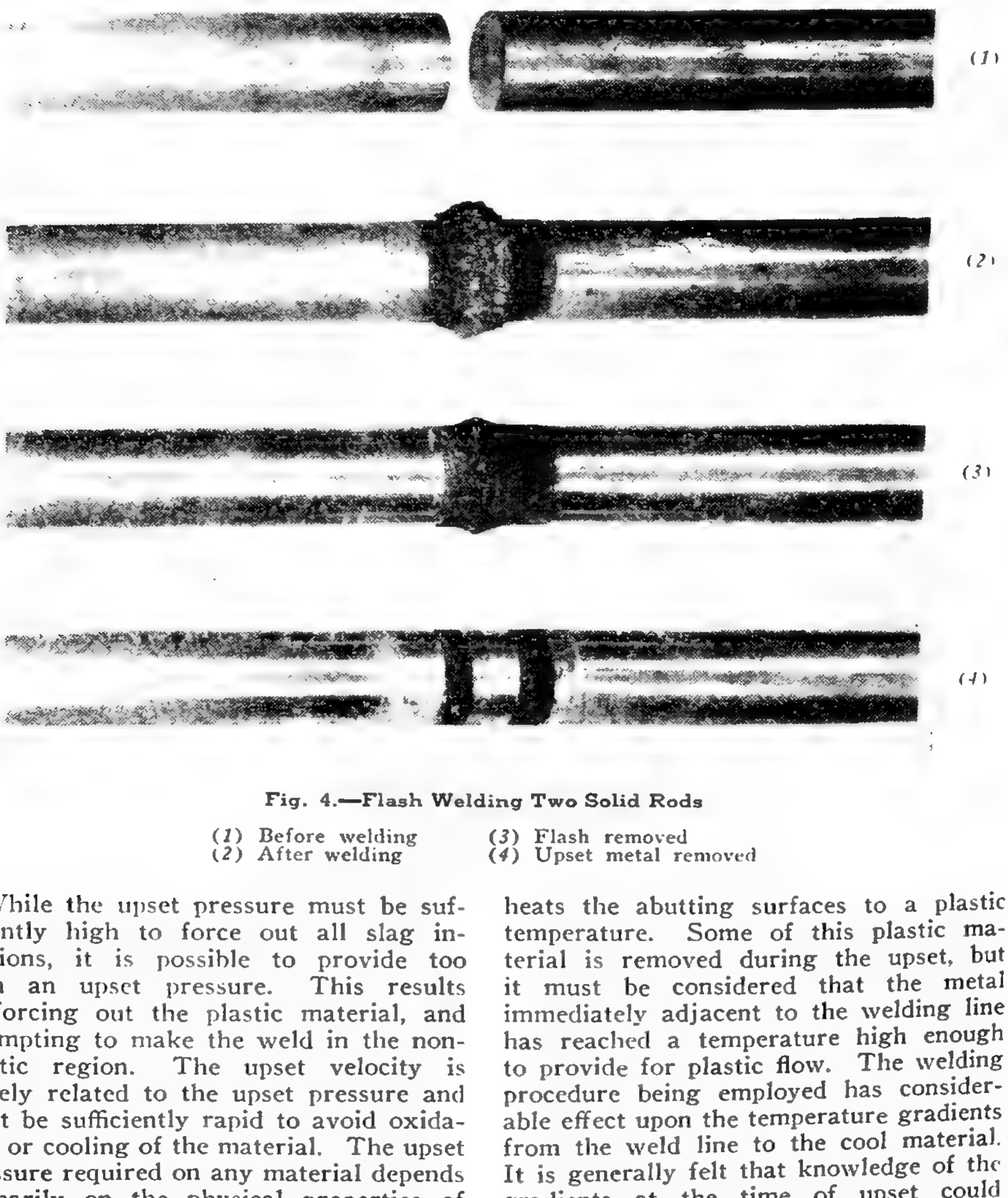


Fig. 4.—Flash Welding Two Solid Rods

(*1*) Before welding
(*2*) After welding
(*3*) Flash removed
(*4*) Upset metal removed

While the upset pressure must be sufficiently high to force out all slag inclusions, it is possible to provide too high an upset pressure. This results in forcing out the plastic material, and attempting to make the weld in the nonplastic region. The upset velocity is closely related to the upset pressure and must be sufficiently rapid to avoid oxidation or cooling of the material. The upset pressure required on any material depends primarily on the physical properties of the materials being welded.

Values of upset pressures normally used

heats the abutting surfaces to a plastic temperature. Some of this plastic material is removed during the upset, but it must be considered that the metal immediately adjacent to the welding line has reached a temperature high enough to provide for plastic flow. The welding procedure being employed has considerable effect upon the temperature gradients from the weld line to the cool material. It is generally felt that knowledge of the gradients at the time of upset could considerably assist in determining optimum welding conditions, and thus the machine

settings might be predetermined without the necessity of making a considerable number of samples. Since the material being welded is heated to a plastic condition, alloy or high-carbon steels will tend to harden unless the cooling rate is retarded. This may be done by adding postheating to the welding cycle or preheating prior to starting the welding operation or both.

In some instances it is necessary to completely heat treat the assembly after welding in order to obtain a uniform structure and hardness. Further information on welding various materials is given in the section of this chapter pertaining to materials welded.

Due to flashing and upsetting there is a certain amount of material lost when using this process. Since it is desired that the upset pressure be consistently maintained, it is usually necessary to have the parts to be welded made to close tolerances. In any instance, the tolerances of the parts should be closer than is expected of the assembly after welding. Tables are included in the Recommended Practices shown in this chapter giving the total amount of stock lost when welding various sizes and shapes. Due to the slow cooling and the symmetrical shapes usually flash welded, the problem of residual stresses at the conclusion of the welding operation is not a major problem. In some instances as when welding tubular sections to heavy forgings, residual stresses may be developed. In these cases, it may be again necessary to stress relieve or completely heat treat after welding.

Weld Quality

As might be expected welds made on manually-operated machines will show large variations in the welding cycle, depending on the skill of the operator. The best method of checking to determine whether or not the weld has been properly made is by means of a cross section which has been cut and etched to determine whether or not any defects are present.

Figure 5 (*a*) illustrates the outward appearance of a weld which has been properly made, Fig. 5 (*b*) a weld which cracked longitudinally due to insufficient heat in the material at the time of upset and Fig. 5 (*c*) a weld upset with insufficient heat. It should be noted that the slope of the upset material in Fig. 5 (*c*) is much flatter than the slope of the upset material on the weld properly made. Excessive upset pressure would result in an appearance similar to Fig. 5 (*c*) except that the volume of upset material would be greater.

The effect of flashing and upsetting under improper conditions was discussed earlier in this chapter. Figure 6 summarizes in tabular form the effects of the more important variables involved. In this table each variable is considered individually, although in certain instances more than one might cause the same effect.

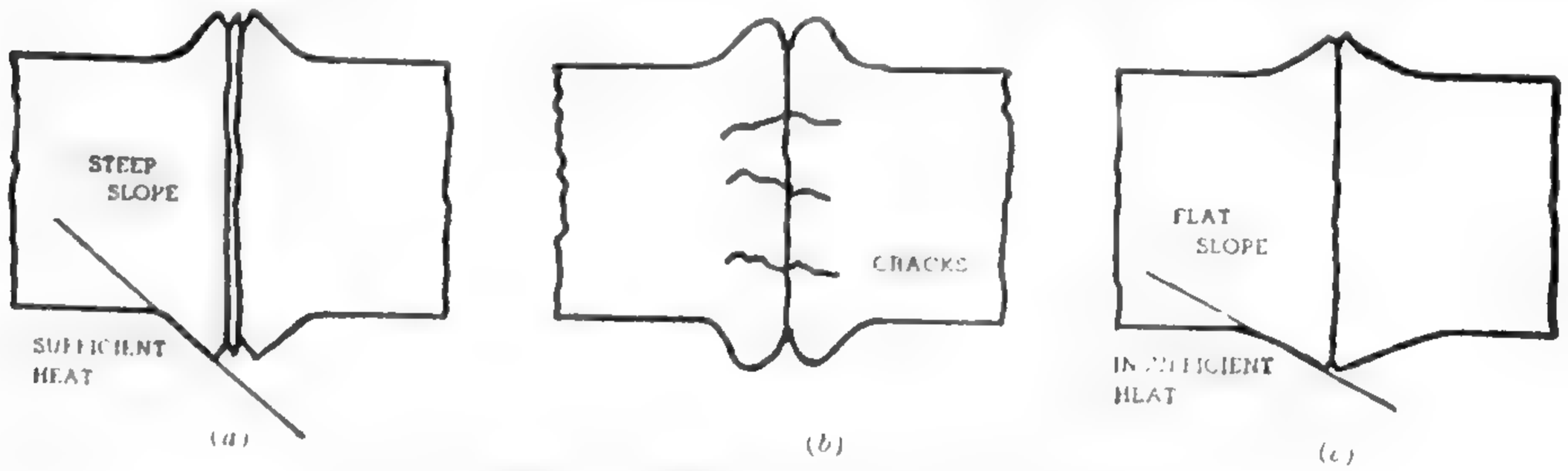


Fig. 5.—Surface Indications of Flash Weld Quality

In order to maintain consistent quality, it is necessary that both parts to be welded and the dies used in the welding machines be designed properly. In order to hold to close dimensions in flash welding, it is necessary to clamp the pieces so that they will not slip during the upset pressure. These clamps and dies must be designed so that they will carry sufficient current to the parts being welded and distribute this current properly. Further information concerning the design of flash welded assemblies and references to the tooling necessary for flash welding is included in the portion of this chapter referring to design.

The metallurgical quality of flash welded assemblies is discussed in the

section of this chapter on Metallurgical Considerations.

Design

General.—Flash welding is a highly satisfactory welding process provided the parts are properly designed for its use. the welded assemblies be held to very close tolerances, and it should be remembered that the dimensional accuracy obtainable with the process, while it is quite close, cannot be better than that of the pieces prior to welding. Therefore, when close tolerances are required in the

WELD VARIABLES		TOO HIGH	TOO LOW
FLASHING VARIABLES	Energy	Deep craters are formed which cause pockets and inclusions in weld. Cast metal in weld.	Tendency to freeze. Material not plastic enough for proper upset.
	Rate	Tendency to freeze.	Intermittant flashing which makes it difficult to develop sufficient heat in the material for proper upset.
	Time	Material too molten to upset properly.	Not plastic enough for proper upset - Parting line of completed weld below surface of work.
UPSETTING VARIABLES	Current	Burning or oxidation of the material even to the extent of blowing out metal. Excessive deformation.	Longitudinal cracking through weld area - Inclusions and voids not properly forced out of weld.
	Travel or Pressure	Tendency to squeeze out all plastic material and make the weld in material which is too cold. Flow lines bent parallel to weld. Low fatigue strength.	Failure to squeeze defects out of weld - Cast metal retained in weld - Parting line of weld below surface of work - Oxides, inclusions and voids in weld.

Fig. 6.—Effect of Variables on Flash Weld Quality

In designing for flash welding it is necessary to recognize the importance of obtaining adequate die contact for current flow into the work-pieces. This involves provisions for a sufficient area of electrode contact and for a clean surface condition. These areas must be clean in order to conduct the high currents without flashing or arcing at the electrodes. Arcing burns the welding dies and results in high replacement costs.

In many instances, it is desired that welded assembly, it is essential that the locating points which are used in the welder dies should be held to the same, or closer, tolerances than are desired on the completed assembly. Closer tolerances are obtainable with flash welding than may be obtained consistently by any other welding process, the accuracy in production being influenced by the following factors:

1. Tolerances of the parts before welding.

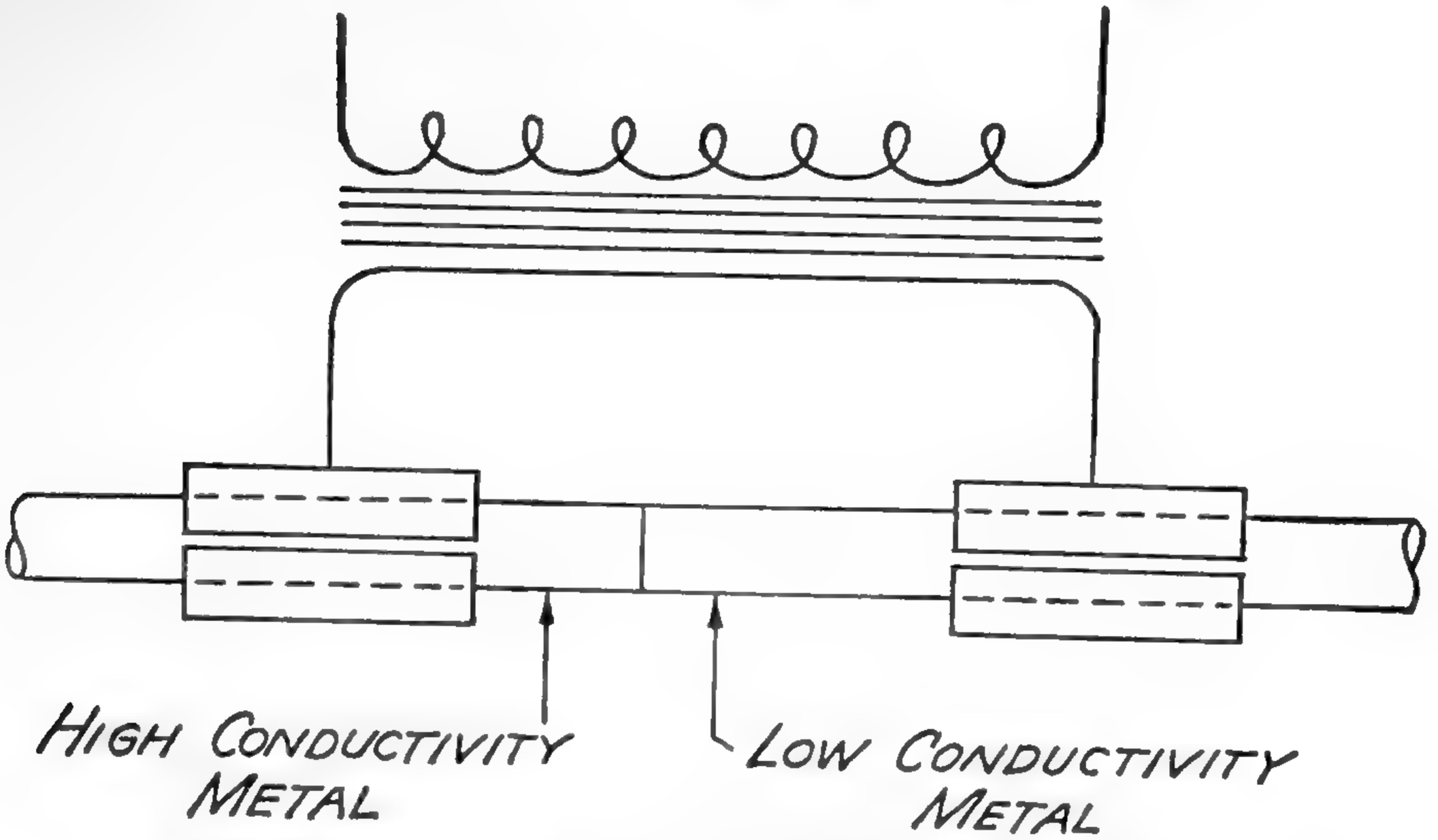


Fig. 7.—Method of Heat Balance by Unequal Extension of Work-Pieces from Dies

2. The rigidity and precision of the welding machine and fixtures.

3. The maintenance given welding electrodes to control normal electrode wear.

4. The care used in loading the work in the welding machine.

Heat Balance.—In order to make a good flash weld it is necessary that the same plasticity be obtained in the two parts being welded. Under certain conditions this may be difficult due to either a difference in the cross-sectional area of the two parts or to differences in the heat conductivities of the two parts. In such instances several techniques may be used to obtain proper heat balance. One method is to extend the part which does not heat up as fast farther out of the dies, as illustrated in Fig. 7. Another method is by an unequal beveling of the two parts as indicated in Fig. 8. In extreme cases it is possible to preheat one piece, either before it is put in the welding machine or while it is already in the machine by use of a bridge (Fig. 9). Such a bridge is usually made of copper and is designed to short circuit one work-

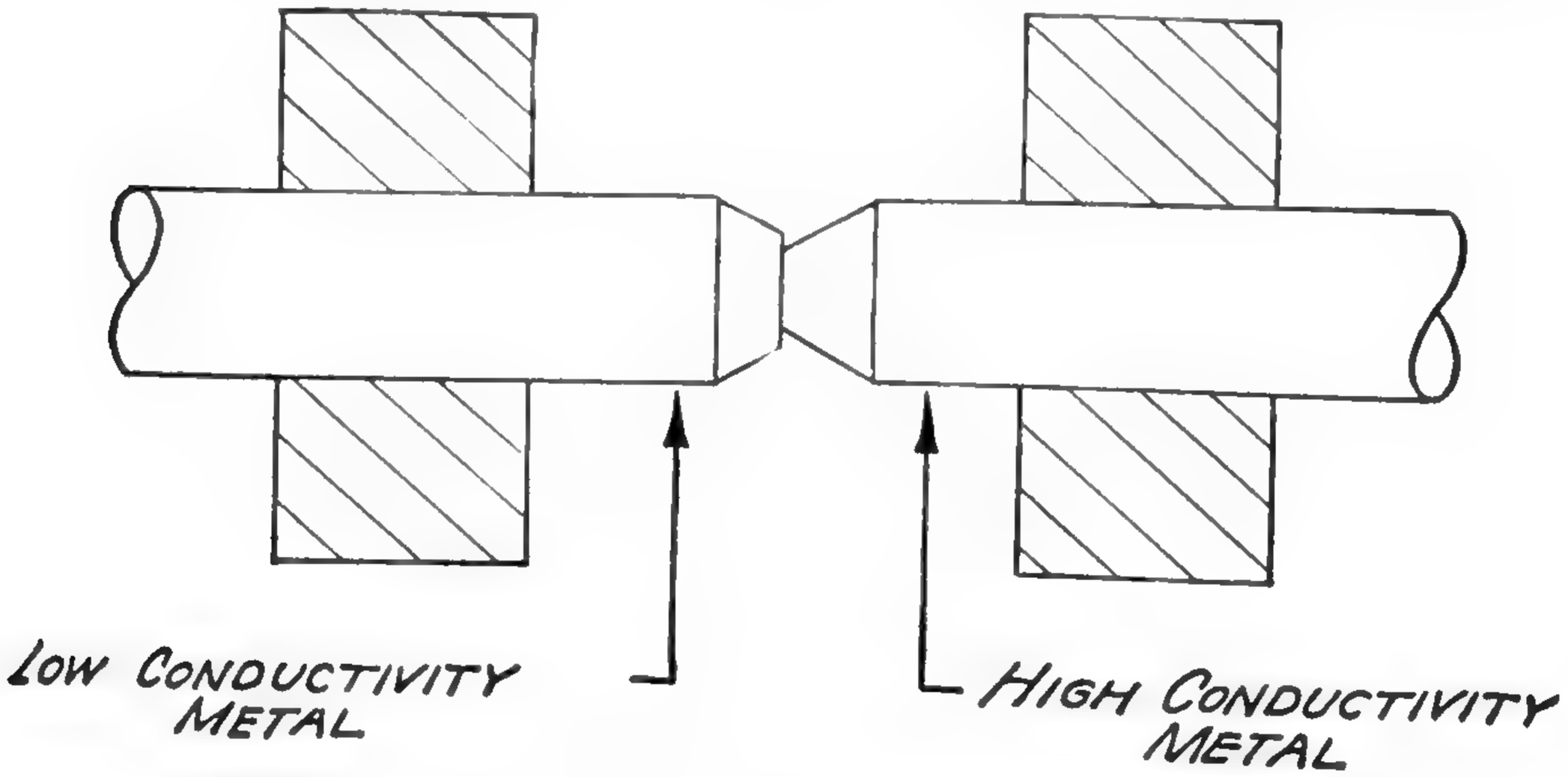


Fig. 8.—Method of Heat Balance by Unequal Beveling of Work-Pieces

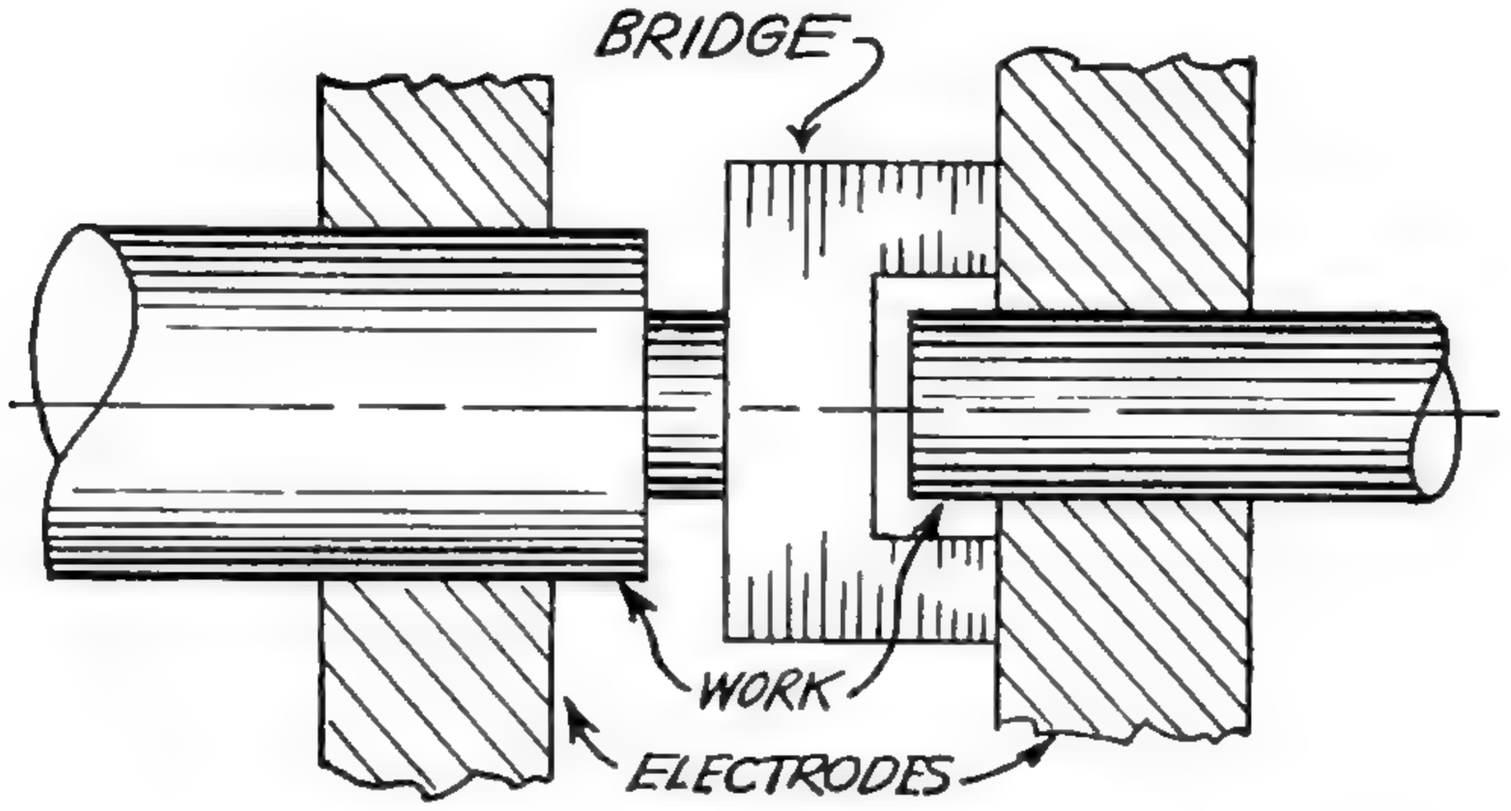


Fig. 9.—Method of Heat Balance by Use of Copper Bridge

piece in the machine in order to preheat the other piece. After this preheating is accomplished the bridge is removed and the pieces are welded in the usual manner.

It should be remembered in the designing of flash-welded assemblies that this heat balance should be designed into the parts rather than obtained by special procedures during the welding operation.

When welding heavy sections it is often advisable to bevel the end of at least one part in order to facilitate the starting of flashing. By means of such beveling, it is possible in some cases to eliminate the necessity for preheating or flashing at a higher than normal voltage for the first part of the flashing period. Illustrations of this type of beveling are shown in Fig. 10 along with suggested dimensions.

It is of prime importance that the surfaces to be welded should line up properly in the welding machine so that the heat generated by flashing is the same over the entire contact area. Should the parts be out of alignment, flashing will only occur in the sections where contact is obtained, and at the time of upset the parts will tend to slip past each other on the cold metal, as illustrated in Fig. 11. In production it is sometimes impossible to hold the tolerances of parts to be welded so that no misalignment occurs. This item should be given careful consideration in the design of the parts to be welded and of the tooling for welding them, especially when the ratio of the length to the width of the sections being welded is high.

In designing a flash-welded assembly, it is necessary to allow extra stock for flashing, and in most cases the sections to be joined should be approximately the same. It is also essential that the provisions made for clamping the pieces enable the welding dies to hold the parts in proper alignment.

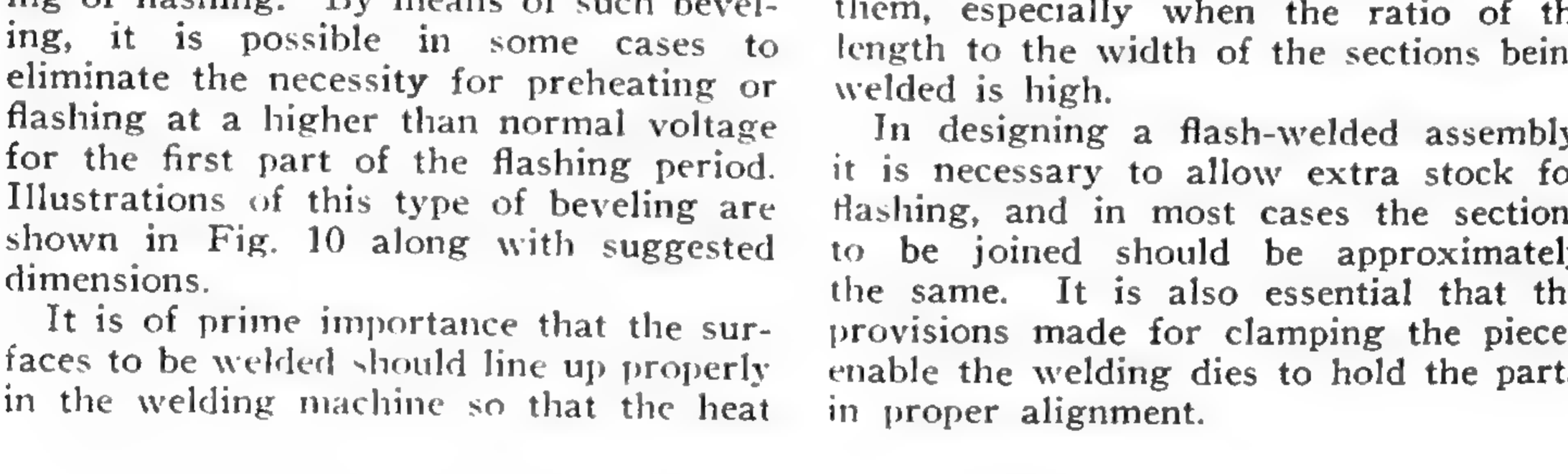


Fig. 10.—End Preparation for Heavy Pieces to Facilitate Flashing

When flash welding shafts, provision should be made for the removal of any deep centers on the welding surfaces which have been used for machining purposes. If deep centers are left in the parts, difficulty with voids or poor fusion will be encountered in the finished weld.

Clamping.—In the welding of certain types of assemblies, it is necessary to maintain the upset pressure with clamps and without the aid of a backup. However, when possible the pieces of work should be backed up by means of fixed stops on the platens and the upset pressure transmitted through these stops. With the use of backups, the clamping pressure on the electrodes need only be sufficient to provide good electrical contact for the welding current and to maintain alignment of the work. Under these conditions, it is usually not necessary to have more than 3000 to 4500 lb. clamping pressure per sq. in. of welded area. In applications such as the welding of rings, where it is impossible to use backups, the clamps must grip the work with sufficient force to prevent slippage when the upset pressure is applied. Under these conditions, it is necessary to consider the upset pressure in relation to the coefficient of friction between the work-piece and the electrodes or jaws. It has been common practice to assume a ratio of $2^1/_2$ to 3 times the upset force for determining the clamping force. When one of the clamp jaws is made of steel, and slight markings on the work are not objectionable, serrations or teeth may be placed on the face of the clamping dies. When welding stainless steels, clamping pressure approximately 50% higher than for mild steel must be used due to the lower coefficient of friction.

In the welding of rings of any design such as wheels, ring gears, etc., the application must be carefully analyzed to determine whether or not it can be satisfactorily flash welded. Consideration must be given to the fact that welding current will shunt around the solid section of the ring thus cutting down the effective welding current. The amount of this shunting action, of course, depends upon the ratio of the length of the ring to the area being welded. It is also necessary to recognize the fact that the ring must be deformed to a smaller diameter during the welding operation, which naturally requires additional pressure. On small rings, it is particularly difficult to use adequate clamping dies due to interference of the closed side of the ring.

Certain recommendations are made in Table 1 as to the maximum length of joint for flash welding flat sheets of various thicknesses. Similar recommendations are made in Table 2 for the maximum diameters to be used when flash welding tubing of various wall thicknesses. These recommendations or limitations do not infer that it is impossible to increase the weld lengths or tube diameters as specified. The recommendations are not intended to include laboratory procedures or to require a high degree of electrode maintenance in production. They are simply a statement of recommended practices for normal parts preparation, dies and welder maintenance, etc.

Fig. 11.—Illustrating Effect of Alignment

Flash Removal.—It is frequently necessary to remove both the flash and the extruded material after the weld is made. In some cases this is necessary only for the sake of appearance. The joint is somewhat stronger in tension before the flash is removed because of the added rigidity of the upset material; however, the notch effect at the weld line may cause a reduction of fatigue strength. When the design of the parts indicates that reinforcement is beneficial, a por-

tion of the upset material may be retained. This material may be removed in a number of ways, the most popular being by means of the following:

1. Air chisels.
2. Machine tools and cutting tools.
3. Grinding wheels.
4. High-speed burring wheels.
5. Die trimming.
6. Oxygen machining or cutting torch.
7. High-speed sander.
8. Flash trimmer.

The above methods are in use on various applications, the choice depending on the type of operation. When welding alloys steels, the removal of flash by means of cutting tools is often difficult due to the hardness of the flash, and either grinding or oxygen cutting is usually employed. It is generally easier to remove the flash immediately after welding while the material is still hot.

Tooling.—In flash welding, the welding dies usually carry current to the parts to be welded, as well as clamping them. It is, therefore, necessary to use a die material of the right physical properties to properly accomplish the clamping, as well as proper electrical characteristics to carry current to the parts. Many materials have been developed for this use. A description of them will be found in Chapter 15. In the design of these welding dies, it is important that adequate water cooling be provided to avoid changes in mechanical properties caused by elevated temperatures.

Inspection and Testing

The most prevalent method of inspecting flash welds is by means of visual inspection of the weld. It is usually necessary that the appearance be judged prior to removing the flash and upset material, due to the fact that the removal of this material often tends to hide defects. There are several other non-destructive inspection methods which have been used with varying degrees of success, but none of which actually will locate all types of defects. Magnetic particle inspection will indicate small inclusions and discontinuities, as well as cracks, provided that they are of sufficient size and in such a location that an indication may be obtained. Naturally, magnetic inspection is not applicable on non-magnetic materials and its use has been rather limited for the inspection of flash welds with the exception of certain critical joints wherein all steps possible are taken to obtain 100% performance.

Table 1—Recommended Maximum Joint Lengths for Flash Welding Flat Sheet

Sheet Thickness, In.	Max. Joint Length, In.	Sheet Thickness, In.	Max. Joint Length, In.
0.010	1.00	0.060	25.00
0.020	5.00	0.080	35.00
0.030	10.00	0.100	45.00
0.040	15.00	0.125	57.00
0.050	20.00	0.187	88.00

Radiographic inspection of flash welds to date has not been wholly satisfactory because small defects which are known to be detrimental cannot be brought out on the radiograph. Radiographic technique for the location of flash welding defects may be developed in the future, but at the present time its application is extremely limited.

In some cases good inspection is automatically obtained by stressing the material well above the yield point in sizing operations. Where uniform high strength is imperative, the assembly may be proof loaded to design specification. Destructive testing of a percentage of the assemblies welded has also been employed with good results.

Macrographic examination is very satisfactory for determining whether or not the machine is properly set up to weld a particular assembly but is not usually employed as a regular inspection procedure.

When automatic welding machines are used, it is most important to make sure that the setup remains constant after

production starts, because there is little that the operator can do to influence welding conditions or weld quality.

Flash welds may be tested by most means available for testing the base properties of the metal. The following properties of a flash weld may be investigated in addition to those previously mentioned.

1. Hardness.
2. Tension.
3. Tension impact.
4. Fatigue.
5. Bending.
6. Cupping.
7. Corrosion resistance.
8. Metallographic structure.

With the proper application of the flash-welding process, it is possible to obtain high joint efficiency, provided the joint has been properly designed and the proper steps have been taken to obtain a metallurgically sound weld area.

The reliability and speed of the operation as well as the fact that the training of operators is not difficult (when using the automatic types of machines), have done much toward making flash welding practical on high production applications. Therefore, development of applications for the process has been accelerated, and indications are that its importance in production will continue to grow. For further information on methods of inspection and tests see Chapter 42.

EQUIPMENT USED

Machines

Flash-welding machines may be either manual, semi-automatic or fully automatic in their operation. Most of the equipment being manufactured today is either semi-automatic or fully automatic and is designed to handle only the basic cycle referred to early in this chapter. Many of the lighter flash-welding machines are provided with platen motion by means of a variable speed cam driven by an electric motor through a speed reducer. Many of the heavier machines are hydraulically operated and equipped so that the speed of the platen motion may be changed.

In fully manual operation, the operator controls the speed of the platen from the time that flashing is initiated until the upset is completed. In semi-automatic operation, the operator usually initiates flashing manually after which the rest of the cycle is completed automatically. In fully automatic operation, the pieces are loaded into the machine after which the cycle is completed automatically.

Further discussion of flash-welding machines is given in Chapter 15 of this HANDBOOK.

Controls and Auxiliary Equipment

Electrical controls on flash-welding machines are primarily designed to start and stop the current supply to the welding transformer and to sequence the motion of the movable platen. The contactor for making and breaking the power supply may be either magnetic or electronic in operation. Although the use of electronic contactors is becoming more general, most installations still utilize magnetic equipment. The controls for automatic flash-welding machines in some instances are capable of sequencing all of the steps listed earlier in this chapter. However, most of the control equipment in service is designed to use the basic cycle without preheat, postheat or any other special operations.

Further information concerning controls and auxiliary equipment for flash-

Table 2—Recommended Maximum Diameters for Flash Welding Tubing

WALL THICKNESSES, IN.	MAX. TUBING DIAMETER, IN.	WALL THICKNESSES, IN.	MAX. TUBING DIAMETER, IN.
0.020	0.50	0.125	4.00
0.030	0.75	0.187	6.00
0.050	1.25	0.250	9.00
0.062	1.50	0.375	15.00
0.080	2.00	0.500	20.00
0.100	3.00		

welding machines is included in Chapter 15 of this HANDBOOK.

COMMON APPLICATIONS

Merits and Limitations

In recent years flash welding, wherein the heat is generated by the *flashing* action has come to be much more widely used than upset welding, partly because it makes possible the end-to-end welding of sheets and other extended sections, and also because it affords a number of distinct advantages. These include:

1. Higher weld strength.
2. Special preparation of weld surfaces not generally necessary.
3. Lower instantaneous power demand.
4. Lower power consumption.
5. Higher production rate.
6. Smaller upset.
7. Better heat concentration.
8. Dissimilar metals may be welded since flashing may be continued until both metals reach their widely varying individual fusing temperatures. (See discussion of Heat Balance earlier in this chapter.)

Flash welding, with these main features, has replaced upset welding in many operations. However, it should be noted that there are certain advantages in upset welding that make it preferable for some work.

1. The spatter of flash welding is not present.
2. There is very little ragged extrusion of material.
3. Usually the upset is smooth and symmetrical, although more pronounced.

Materials Welded

Flash welds are most commonly employed in joining two pieces of metal end to end or in welding one piece of material to a projecting part of another piece. Typical applications include the welding of two shafts, tubes or strips of steel together or the welding of a forging or casting either to another forging or to some standard section. Another application is in welding strips or bars to form rings, such as wheel rims. For any of these applications to be practical, it is necessary that the cross-sections of the two pieces being joined be nearly identical. In most instances either upset or flash welding could be utilized, but for the reasons listed previously, the use of flash welding is usually preferable, especially on heavier sections, on extended sections and when dissimilar metals are involved.

In the following discussion, the weldability of various metals by the flash-welding process is considered from the standpoint of the number of steps which are necessary to insure good welds. Steels of low hardenability may be welded without preheat or postheat with an excellent probability of obtaining consistently good results. As the hardenability of the steel increases, it is necessary to resort to combinations of preheat and postheat to make the welded joint as good as that obtained in steels of lower hardenability. It is generally considered that flash welding is satisfactory on almost all types of steel, provided the proper steps are taken to obtain a sound joint. Combinations of steels such as high-speed tool steel to low-carbon steel are welded satisfactorily, although it is usually necessary to employ special procedures to equalize the differences in hardness, fusion temperature, electrical and thermal conductivity, geometry and crack-sensitivity. Most of the nonferrous metals are welded satisfactorily. The procedures and techniques required are varied and any particular case must be considered individually.

Flash welding of cast iron has been successful only to a limited extent. Lead, tin, zinc, antimony, bismuth and alloys in which they are the principal constituents, as well as copper alloys in which any of the above metals are present in large percentages, are not generally recommended for flash welding application. With these exceptions, the process usually can be considered applicable to almost any combination of metals, regardless of their dissimilarity, though the necessity for special procedures and techniques might make certain applications impractical.

Industries Using Flash Welding

The flash-welding process is being used generally by almost all the fabricating industries in the United States. It is probably most important in industries with high production schedules. Its use in job shop fabrication or industries with low production is limited, due to the expense of manufacturing tooling and establishing welding procedures.

Reference is made in Chapters 54 and

55 to the use of flash welding in conjunction with manufacturing automotive and aircraft products. The process is also used widely in the manufacture of household appliances, refrigerators, farm implements, etc.

RECOMMENDED PRACTICES FOR FLASH WELDING

In correlating the material for these Recommended Practices, it is necessary to define the process variables and then to specify the method of measurement of some of these variables. Such definitions with the accompanying definition chart are given in subsequent paragraphs.

When employing these practices and considering the definitions, it should be realized that neither all flash-welding equipment nor all flash-welding schedules make use of all the listed variables.

The most common applications use no preheating, dual flashing currents or post-heating, but consist of flashing at a single current, followed by upsetting. Most equipment now in production performs only these two functions.

The use of these data is intended to aid in establishing successful welding procedures. No inference is intended that variations cannot be made from these data, but the exact degree of variation which may be made and still produce welds of optimum quality is not known.

Definitions

See Flash-Welding Definitions Chart, Fig. 12.

7.1—*Weld Line* is the plane of fusion of the welded parts.

7.2—*Flash* is the extraneous material which is thrown and extruded from the weld line during the flashing and upsetting actions.

7.3—*Initial Die Opening* (A, in.) is the distance between the dies when the work-pieces first contact.

7.4—*Material Lost* (B, in.) is the total length of material that is used in making the weld.

7.5—*Final Die Opening* (C, in.) is the distance between the dies at the completion of the weld.

7.6—*Total Flash-Off* (D, in.) is the total length of material that is lost in flashing.

7.7—*Manual Flash-Off* (E, in.) is the length of material that is lost in flashing while the flashing is controlled manually.

7.8—*Automatic Flash-Off* (F, in.) is the length of material that is lost in flashing while the flashing is controlled automatically.

7.9—*Preheating Loss* (G, in.) is the length of material that is lost as the result of the preheating action.

7.10—*Total Upset* (H, in.) is the length of material that is lost as the result of the forging action.

7.11—*Material X Lost* (J, in.) is the length of Material X that is used in making the weld.

7.12—*Material Y Lost* (K, in.) is the length of Material Y that is used in making the weld.

7.13—*Initial Extension, Material X* (L, in.) is the dimension from the die which clamps Material X to that point on Material X which first contacts Material Y.

7.14—*Initial Extension, Material Y* (M, in.) is the dimension from the die which clamps Material Y to that point on Material Y which first contacts Material X.

7.15—*Final Extension, Material X* (N, in.) is the dimension from the die which clamps Material X to the Weld Line at the completion of the weld.

7.16—*Final Extension, Material Y* (P, in.) is the dimension from the die which clamps Material Y to the Weld Line at the completion of the weld.

7.17—*Travel at I_1* (Q, in.) is the dimension the movable platen (Material Y) travels during the flashing current, I_1.

7.18—*Travel at I_2* (R, in.) is the dimension the movable platen (Material Y) travels during the flashing current, I_2.

7.19—*Spring-Back* (in.) is the deflection of the welding machine when making the weld.

7.20—*Preheating Time* (sec.) is the time during which preheating is taking place.

7.21—*Manual Flashing Time* (sec.) is the time during which flashing by manual control is taking place.

7.22—*Automatic Flashing Time* (sec.) is the time during which flashing by automatic control is taking place.

7.23—*Time at Flashing Current I_1* (sec.) is the time during which flashing with current I_1 is taking place.

7.24—*Time at Flashing Current I_2* (sec.) is the time during which flashing with current I_2 is taking place.

7.25—*Upsetting Current Time* (sec.) is the time during which upsetting current flow is taking place.

7.26—*Upsetting Time* (sec.) is the time during which upsetting is taking place.

7.27—*Welding Time* (sec.) is the

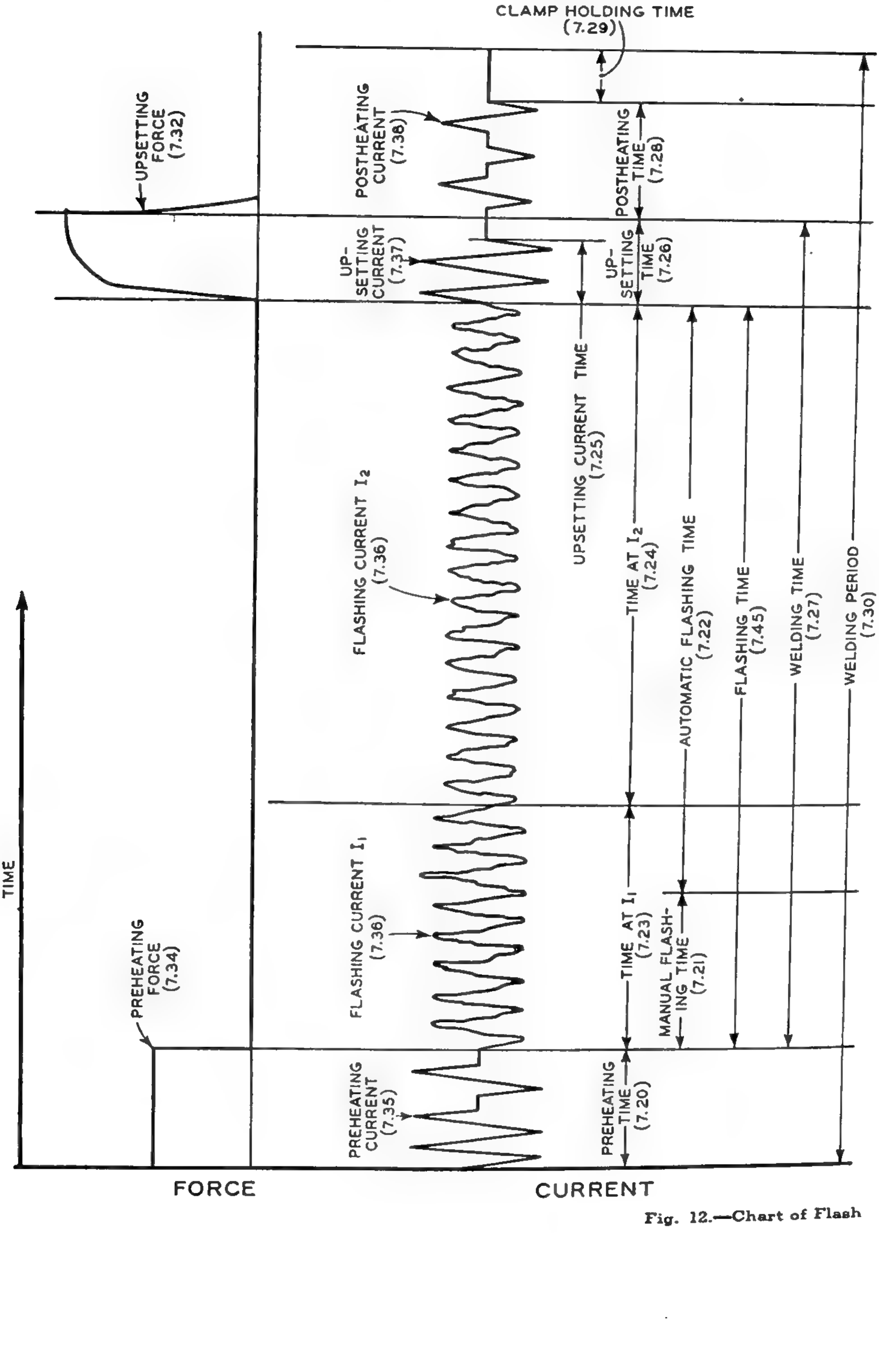
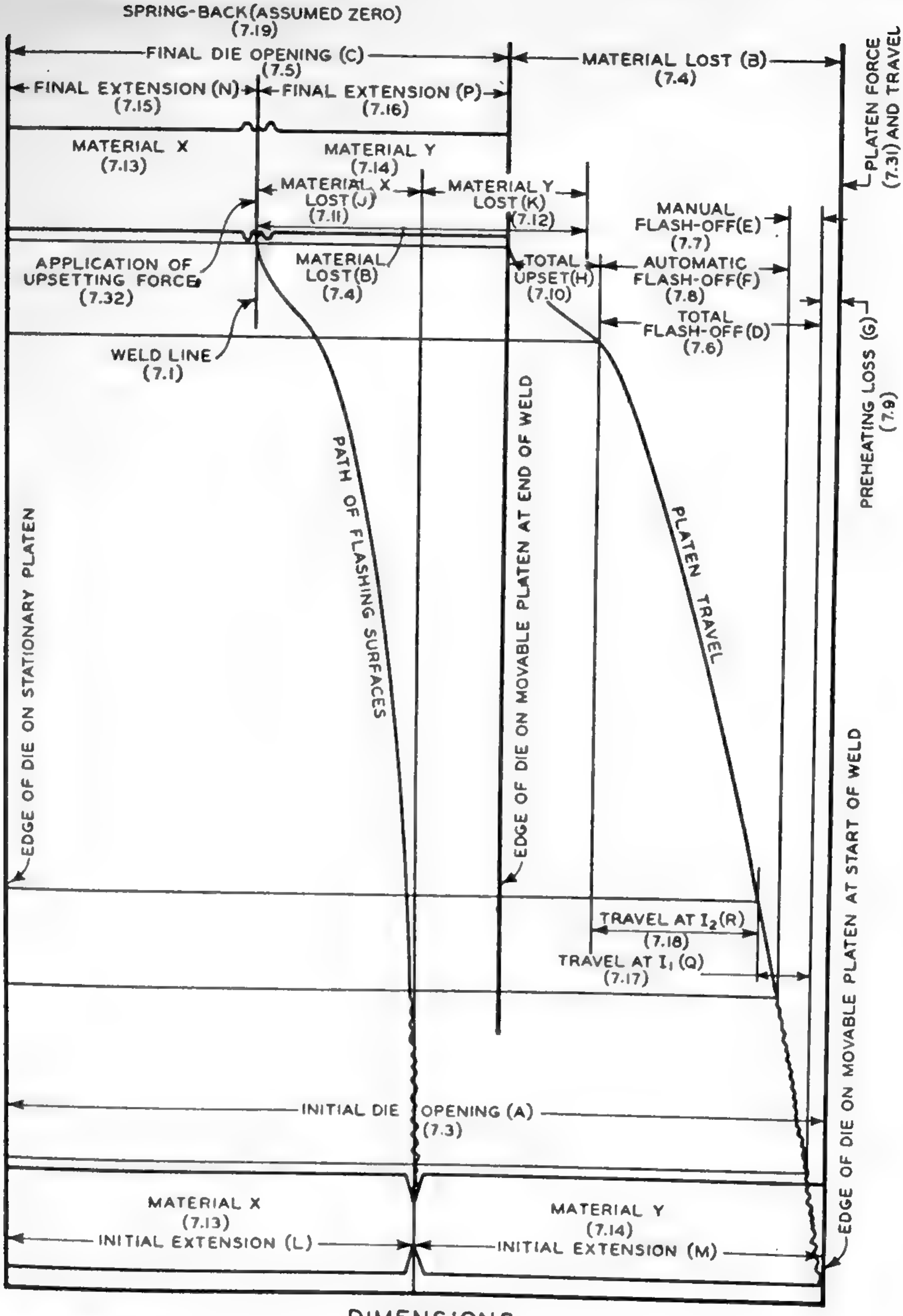


Fig. 12.—Chart of Flash



DIMENSIONS

Welding Definitions

time during which flashing and upsetting are taking place.

7.28—*Postheating Time* (sec.) is the time during which postheating is taking place.

7.29—*Clamp-Holding Time* (sec.) is the time measured from the end of the postheating time (or end of upsetting time when no postheat is used) to the time at which the clamping force is released from the work-pieces.

7.30—*Welding Period* (sec.) is the time that elapses from the start of the preheating time to the end of the clamp-holding time.

7.31—*Platen Force* (lb.) is the force available at the movable platen to cause upsetting. This force may be dynamic, theoretical or static.

7.32—*Upsetting Force* (lb.) is the force exerted at the welding surfaces during upsetting.

7.33—*Clamping Force* (lb.) is the force exerted on the dies by the clamping system.

7.34—*Preheating Force* (lb.) is the force exerted on the welding surfaces during preheating.

7.35—*Preheating Current* (rms. amp.) is the current that flows through the work-pieces during preheating.

7.36—*Flashing Current* (amp.) is the current that flows through the work-pieces during the flashing.

7.37—*Upsetting Current* (rms. amp.) is the current that flows through the work-pieces during upsetting.

7.38—*Postheating Current* (rms. amp.) is the current that flows through the work-pieces during postheating.

7.39—*Secondary Voltage* (E, rms. volts) is the open-circuit voltage of the welding transformer measured on the secondary side.

7.40—*Load Voltage* (V, volts) is the voltage across the work-piece while welding and postheating.

7.41—*Instantaneous Rate of Flash-Off* (in. per sec.) is the instantaneous velocity of one work-piece relative to the other during flashing action and is the first derivative of such motion at a specified position.

7.42—*Average Rate of Flash-Off* (in. per sec.) is the average velocity of one work-piece relative to the other during the entire flashing action.

7.43—*Instantaneous Velocity of Upset* (in. per sec.) is the instantaneous velocity of one work-piece relative to the other during upsetting action and is the first derivative of such motion at a specified position.

7.44—*Average Velocity of Upset* (in. per sec.) is the average velocity of one work-piece relative to the other during the entire upsetting action.

7.45—*Flashing Time* is the time during which the flashing action is taking place.

For additional definitions see Chapter 1.

Dimensional Measurements

Dimensions of *Material Lost; Material X Lost; Material Y Lost; Initial Extension, Material X; Initial Extension, Material Y; Final Extension, Material X;* and *Final Extension, Material Y* are usually obtained by scale measurement of the work-pieces before and after welding.

Dimensions of *Initial Die Opening; Final Die Opening; Total Flash-Off; Manual Flash-Off; Automatic Flash-Off; Preheating Loss; Travel at* I_1; and *Travel at* I_2 are usually obtained by scale measurement of such items on the welding machine.

The *Total Upset* is most accurately measured by subtracting the sum of the measurements of *Total Flash-Off* and *Preheating Loss* from the measurement of *Material Lost.* The high speed of upsetting together with the error introduced by *Spring-Back* of the machine makes it difficult to measure the *Total Upset* directly and accurately.

The dimension of *Spring-Back* is difficult to measure directly and fortunately is not important as a weld variable. It assumes more importance as an equipment variable.

Time Measurements

The time intervals of *Preheating Time; Manual Flashing Time; Automatic Flashing Time; Time at Flashing Current* I_1; *Time at Flashing Current* I_2; *Welding Time; Postheating Time;* and *Welding Period* can usually be measured with a stop watch with sufficient accuracy, or can be taken from the chart of a recording instrument such as an oscillograph, recording ammeter, recording wattmeter, cycle counter, etc.

The *Upsetting Current Time* can be taken from the records of an oscillograph or recording ammeter, depending on the length of the time and accuracy desired.

The *Upsetting Time* can be most conveniently taken from the record of a Platen Movement Recorder.

The *Clamp-Holding Time* can be obtained by the use of a dial or chart-type cycle counter.

Force Measurements

The *Platen Force and Upsetting Force* are of a transient nature and are influenced by the method of applying the forces, by friction, by inertia and by the opposing reaction of the material being upset. Consequently, it is difficult to obtain precise measurements of such forces without elaborate strain gages, etc. There are no well-recognized simple approximate methods of measurement in use.

The *Clamping Force* is usually calculated, the effect of friction being considered when making such calculations.

Current Measurements

Preheating Current and *Postheating Current* can be measured by indicating or recording ammeters or oscillographs.

The *Flashing Current* is very irregular due to the flashing action while making a weld. While an oscillograph record is an accurate indication of this current, such records are difficult to analyze readily. Records taken with recording ammeters are usually sufficiently accurate and permit easier analysis to the extent that such records are in common use. To transfer data from one welding schedule to another by means of recording ammeters requires that such ammeters have equivalent damping characteristics. Standard methods are being developed for the calibration of the damping characteristics of recording ammeters.

Upsetting Current can be precisely measured by an oscillograph or by pointer-stop ammeters for a slightly less, but generally satisfactory, degree of accuracy.

Voltage Measurements

Secondary voltage can be measured using an indicating voltmeter.

The *Load Voltage* is as irregular as the *Flashing Current* and can be measured by a recording voltmeter.

Rates and Velocities of Flash-Off and Upset

The *Average Rate of Flash-Off* can be calculated from the *Flashing Time* and the *Total Flash-Off*.

The *Instantaneous Rate of Flash-Off*, the *Instantaneous Velocity of Upset* and *Average Velocity of Upset* can be measured by the use of any device which will satisfactorily record mechanical motion and time.

Classification of Steels for Flash Welding

The values of the Upsetting Forces required for various sections of various steels are related to the temperature gradient of the work-pieces in the plastic zone and to the compressive strengths of the steels at these elevated temperatures.

For consideration of applying the flash-welding process to steels, such steels are classified as follows and typical steels of the various classes are given:

Low forging strength steels—This class is typified by SAE 1020, SAE 1112, SAE X1112, SAE X1315, Cor-Ten, Man-Ten, Sil-Ten, NAX 9115, Yoloy, Ductiloy, Cromansil, Republic RDS, etc.

Medium forging strength steels—This class is typified by SAE 1045, SAE 1065, SAE X1335, SAE 3135, SAE 4130, SAE 4140, NE 8442, NE 8640, NE 9440, NE 9540, NE 9640, etc.

High forging strength steels—This class is typified by SAE X4340, SAE 4640, stainless iron (12% chromium type), stainless steel (18–8 type), stainless steel (cutlery type), high-speed steel, Sil-Chrome, special tool, die and austenitic valve stem steels.

Extra high forging strength steels—This class is typified by all steels exhibiting extra high compressive strengths at elevated temperatures such as Timken Alloy, etc.

Flash-Welding Schedules

Flash-welding schedules for welding tubing and flat sheets having thicknesses ranging from 0.010 to 1.00 in. are given in Fig. 13 and Table 3 and cover steels of low and medium forging strength.

Flash-welding schedules for welding solid round, hexagonal, square and rectangular bars having an outside diameter of rounds or minimum dimensions of other sections ranging from 0.050 to 2.00 in. are given in Fig. 14 and Table 4 and cover steels of low and medium forging strength.

These schedules show the necessary dimensions for setting up a flash-welding machine to weld such sections and the total flashing time based on welding without preheating.

No data are available as to the necessary flashing currents, rates and velocities of flash-off and upset required.

When setting up a schedule, the dimen-

sionable variables and flashing time are selected from the tabulations and the welding-machine voltage regulator adjusted to give the lowest secondary voltage, *E*, at which steady and consistent flashing can be obtained. The flashing current resulting from such voltage setting will then be at a satisfactory value.

The secondary voltage, *E*, to obtain this satisfactory flashing current, is dependent on the electrical characteristics of the welding machine being used.

The upsetting forces used for the schedules are dependent upon the class of steel as well as the section being welded.

High Forging Strength Steels—25,000 psi. of weld sectional area.
Extra High Forging Strength Steels—35,000 psi. of weld sectional area.

B. UPSET WELDING

FUNDAMENTALS OF PROCESS

Definition and General Description

Upset welding is a resistance-welding process wherein coalescence is produced, simultaneously over the entire area of abutting surfaces or progressively along a

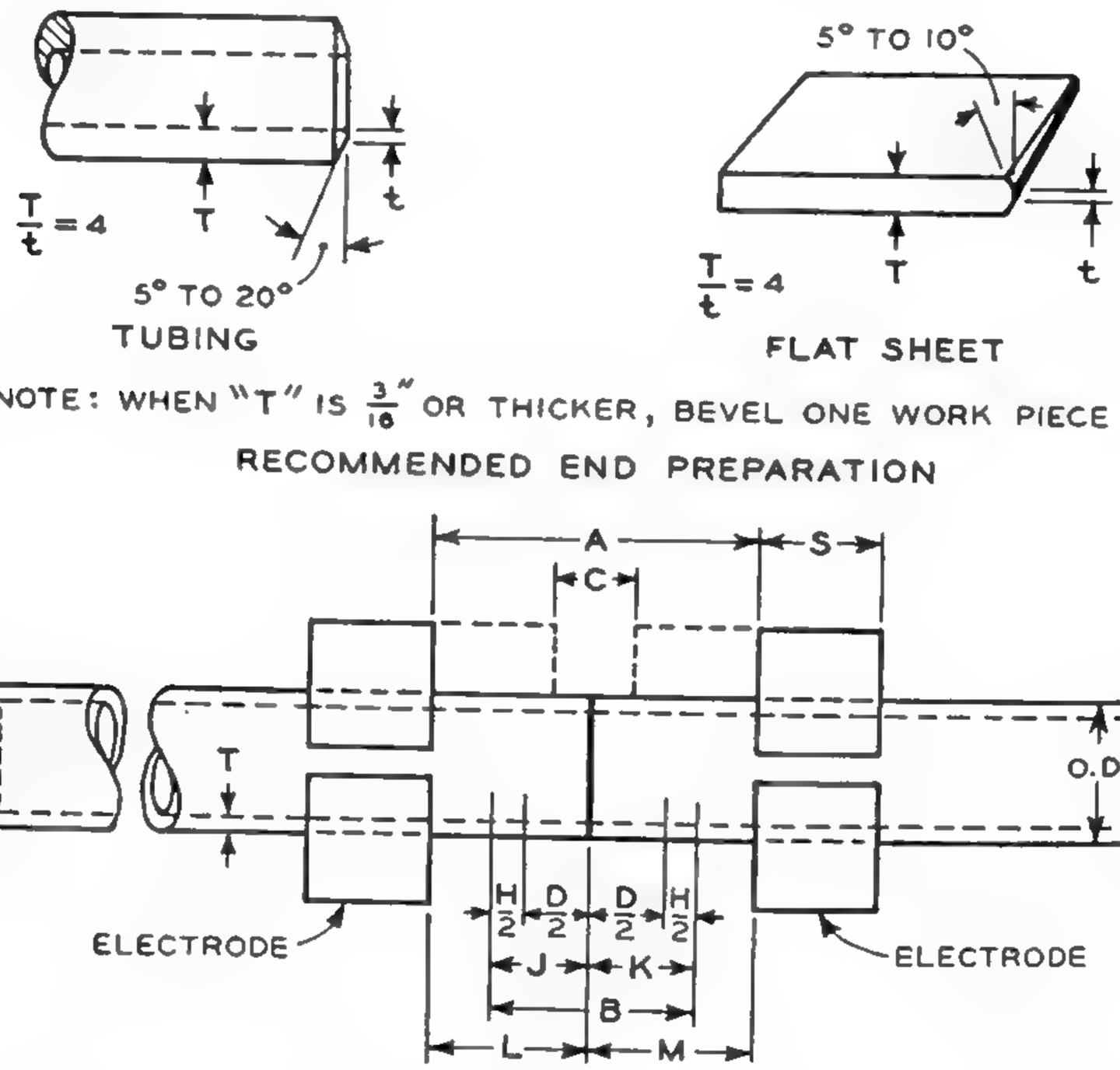


Fig. 13.—Flash Welding of Tubing and Flat Sheets

Experience indicates that the selection of equipment should be based on the following values of recommended platen force and such values are based on the welding heat attained solely by flashing, i.e., no preheating:

Low Forging Strength Steels—10,000 psi. of weld sectional area.
Medium Forging Strength Steels—15,000 psi. of weld sectional area.

joint, by the heat obtained from resistance to the flow of electric current through the area of contact of the abutting surfaces. Pressure is applied before heating is started and is maintained throughout the heating period.

Upset welding is the earliest form of resistance welding. It continues in use for many applications, ranging from the welding of small ferrous and nonferrous

T INCHES	A INCHES	B INCHES	C INCHES	D INCHES	H INCHES	J=K INCHES	L=M INCHES	FLASHING TIME SECONDS
0.010	0.110	0.060	0.050	0.040	0.020	0.030	0.055	0.40
0.020	0.215	0.115	0.100	0.080	0.035	0.058	0.108	0.80
0.030	0.325	0.175	0.150	0.125	0.050	0.088	0.163	1.25
0.040	0.430	0.230	0.200	0.165	0.065	0.115	0.215	1.75
0.050	0.530	0.280	0.250	0.205	0.075	0.140	0.265	2.25
0.060	0.620	0.330	0.290	0.240	0.090	0.165	0.310	2.75
0.070	0.715	0.385	0.330	0.280	0.105	0.193	0.358	3.50
0.080	0.805	0.435	0.370	0.315	0.120	0.218	0.403	4.00
0.090	0.885	0.475	0.410	0.345	0.130	0.238	0.443	4.50
0.100	0.970	0.520	0.450	0.375	0.145	0.260	0.485	5.00
0.110	1.060	0.570	0.490	0.410	0.160	0.285	0.530	5.75
0.120	1.140	0 610	0.530	0.440	0 170	0.305	0.570	6.25
0.130	1.225	0.650	0.575	0.470	0.180	0.325	0.613	7.00
0.140	1.320	0.700	0.620	0.510	0.190	0.350	0.660	7.75
0.150	1.390	0.730	0.660	0.530	0.200	0.365	0 695	8.50
0.160	1.470	0.770	0.700	0.560	0.210	0.385	0 735	9.00
0.170	1.540	0.809	0.740	0.580	0.220	0.400	0.770	9.75
0.180	1.620	0.840	0.780	0.610	0.230	0.420	0 810	10.50
0.190	1.690	0.870	0 820	0.630	0 240	0.435	0.845	11.25
0.200	1.760	0.900	0.860	0.650	0.250	0.450	0.880	12.00
0.250	2.010	1.010	1.000	0.730	0.280	0.505	1.005	16.00
0.300	2.245	1.120	1.125	0.810	0.310	0.560	1.123	21.00
0.350	2.460	1.210	1.250	0.880	0.330	0 605	1.230	27.00
0.400	2.640	1.290	1.350	0.930	0.360	0 645	1 320	33.00
0.450	2 780	1.350	1.430	0.970	0.380	0 675	1.390	38.00
0.500	2.910	1.410	1.500	1.020	0.390	0.705	1.455	45.00
0 550	3.040	1.465	1.575	1.055	0.410	0.733	1.520	50.00
0.600	3.135	1.505	1.630	1.085	0.420	0.753	1.568	56.00
0.650	3.245	1 555	1.690	1.125	0.430	0.778	1.623	63.00
0.700	3.360	1.610	1.750	1.160	0.450	0.805	1.680	70.00
0 800	3.525	1.675	1.850	1.210	0.465	0.838	1.763	83.00
0.900	3.660	1.730	1.930	1.250	0.480	0.865	1.830	97.00
1.000	3.800	1.800	2.000	1.300	0.500	0.900	1.900	110.00

O.D. INCHES	S WITH LOCATOR	S WITHOUT LOCATOR
0.250	0.375	1.00
0.312	0.375	1.00
0.375	0.375	1.50
0.500	0.375	1.75
0.750	0.500	2.00
1.000	0.750	2.50
1.50	1.000	3.00
2.00	1.250	
2.50	1.750	
3.00	2.000	
3.50	2.25	
4.00	2.50	
4.50	2.75	
5.00	2.75	
5.50	3.00	
6.00	3.25	
6.50	3.50	
7.00	3.75	
7.50	4.00	
8.00	4.25	
8.50	4.50	
9.00	4.75	
9.50	5 00	
10.00		

WITHOUT USE OF LOCATOR NOT RECOMMENDED

NOTE:

DATA BASED ON WELDING WITHOUT PREHEAT, AND FOR TWO PIECES OF SAME WELDING CHARACTERISTICS

See Fig. 13 for assembly of parts.

Table 3—Data for Flash Welding Tubing and Flat Sheets

O.D. INCHES	A INCHES	B INCHES	C INCHES	D INCHES	H INCHES	J=K INCHES	L=M INCHES	FLASHING TIME SECONDS
0.050	0.100	0.050	0.050	0.040	0.010	0.025	0.050	0.40
0.100	0.182	0.082	0.100	0.062	0.020	0.041	0.091	0.75
0.150	0.270	0.120	0.150	0.090	0.030	0.060	0.135	1.15
0.200	0.350	0.150	0.200	0.110	0.040	0.075	0.175	1.50
0.250	0.430	0.180	0.250	0.130	0.050	0.090	0.215	1.90
0.300	0.510	0.210	0.300	0.150	0.060	0.105	0.255	2.25
0.350	0.600	0.250	0.350	0.180	0.070	0.125	0.300	2.75
0.400	0.685	0.285	0.400	0.205	0.080	0.143	0.343	3.25
0.450	0.770	0.320	0.450	0.230	0.090	0.160	0.385	3.75
0.500	0.850	0.350	0.500	0.250	0.100	0.175	0.425	4.25
0.550	0.940	0.390	0.550	0.280	0.110	0.195	0.470	5.00
0.600	1.025	0.425	0.600	0.305	0.120	0.213	0.513	5.50
0.650	1.100	0.450	0.650	0.325	0.125	0.225	0.550	6.75
0.700	1.180	0.480	0.700	0.350	0.130	0.240	0.590	7.50
0.750	1.260	0.510	0.750	0.375	0.135	0.255	0.630	8.25
0.800	1.340	0.540	0.800	0.400	0.140	0.270	0.670	9.00
0.850	1.420	0.570	0.850	0.425	0.145	0.285	0.710	9.75
0.900	1.500	0.600	0.900	0.450	0.150	0.300	0.750	10.50
0.950	1.580	0.630	0.950	0.475	0.155	0.315	0.790	11.75
1.000	1.660	0.660	1.000	0.500	0.160	0.330	0.830	13.00
1.050	1.740	0.690	1.050	0.525	0.165	0.345	0.870	14.75
1.100	1.820	0.720	1.100	0.550	0.170	0.360	0.910	16.50
1.150	1.900	0.750	1.150	0.575	0.175	0.375	0.950	18.25
1.200	1.980	0.780	1.200	0.600	0.180	0.390	0.990	20.00
1 250	2.060	0.810	1.250	0.625	0.185	0.405	1.030	22.50
1.300	2.140	0.840	1.300	0.650	0.190	0.420	1.070	25.00
1.400	2.300	0.900	1.400	0.700	0.200	0.450	1.150	30.00
1.500	2.460	0.960	1.500	0.750	0.210	0.480	1.230	38.00
1.600	2.620	1.020	1.600	0.800	0.220	0.510	1.310	45.00
1.700	2.780	1.080	1.700	0.850	0.230	0.540	1.390	54.00
1.800	2.940	1.140	1.800	0.900	0.240	0.570	1.470	63.00
1.900	3.100	1.200	1.900	0.950	0.250	0.600	1.550	75.00
2.000	3.260	1.260	2.000	1.000	0.260	0.630	1.630	90.00

O.D. INCHES	S WITH LOCATOR	S WITHOUT LOCATOR
0.250	0.375	1.00
0.312	0.375	1.00
0.375	0.375	1.50
0.500	0.375	1.75
0.750	0.500	2.00
1.000	0.750	2.50
1 50	1.000	3.00
2.00	1.25	
2.50	1.75	
3.00	2.00	
3.50	2.25	
4.00	2.50	
4.50	2.75	
5.00	2.75	
5.50	3.00	
6.00	3.25	
6.50	3.50	
7.00	3.75	
7.50	4.00	
8.00	4.25	
8.50	4.50	
9.00	4.75	
9.50	5.00	
10.00		

NOT RECOMMENDED WITHOUT USE OF BACKUPS

NOTES:

1. DATA BASED ON WELDING WITHOUT PREHEAT, AND FOR TWO PIECES OF SAME WELDING CHARACTERISTICS
2. VALUES APPLY ONLY WHERE RATIO OF MAXIMUM TO MINIMUM CROSS-SECTIONAL DIMENSION DOES NOT EXCEED 1.5 TO 1.0

See Fig. 14 for assembly of parts.

Table 4—Data for Flash Welding Solid Round, Hex, Square and Rectangular Bars

strips and wire to the welding of longitudinal butt joints in tubing and pipe, and transverse butt joints in heavy steel rings.

Principles of Operation

In the application of the upset welding process, the parts are brought into solid contact as indicated in Fig. 15, and current is passed through the contact area until a sufficiently high temperature is generated to allow the forging of a weld between the two parts. The heat is generated mainly by the contact resistance between the two pieces, and in accordance with Joule's law, $H = KI^2RT$. The contact resistance is a function of the nature of the metals being joined, their surface condition and the unit pressure between them. This resistance is approximately in inverse proportion to the unit contact pressure, provided other factors remain constant. As heat is generated in the parts, however, the contact resistance changes until, when the weld is formed, the contact resistance becomes zero and the entire resistance is the resistivity of the parts. Upset welding differs from flash welding in that no flashing from the abutting surfaces occurs at any time, the heat being developed solely by the resistance between the two pieces.

Generally, the pressure and current are maintained throughout the entire welding cycle, although the pressure is usually started at a low value in order to increase the initial contact resistance between the two parts. This pressure is increased to whatever value is necessary to give a forging squeeze when the welding temperature has been reached. When sufficient upset has been produced, the welding current is cut off and the pressure removed.

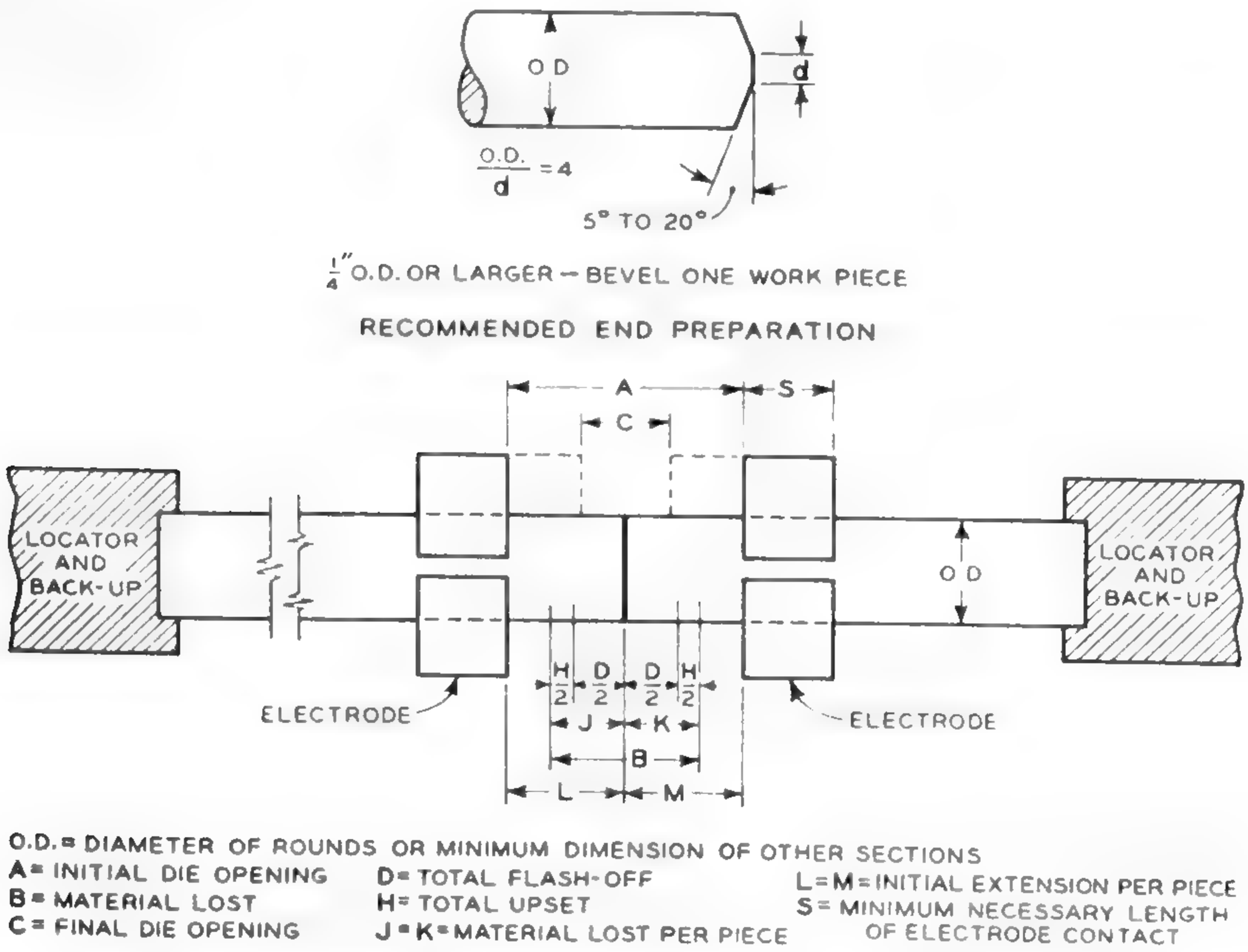


Fig. 14.—Flash Welding of Solid Round, Hex, Square and Rectangular Bars

Following are the essential steps in the sequence of operations to produce an upset weld:

1. Load machine.
2. Clamp work.
3. Apply welding pressure.
4. Apply welding current.
5. Apply upset pressure.
6. Cut off current.
7. Release pressure.
8. Unclamp work.
9. Return platen and unload.

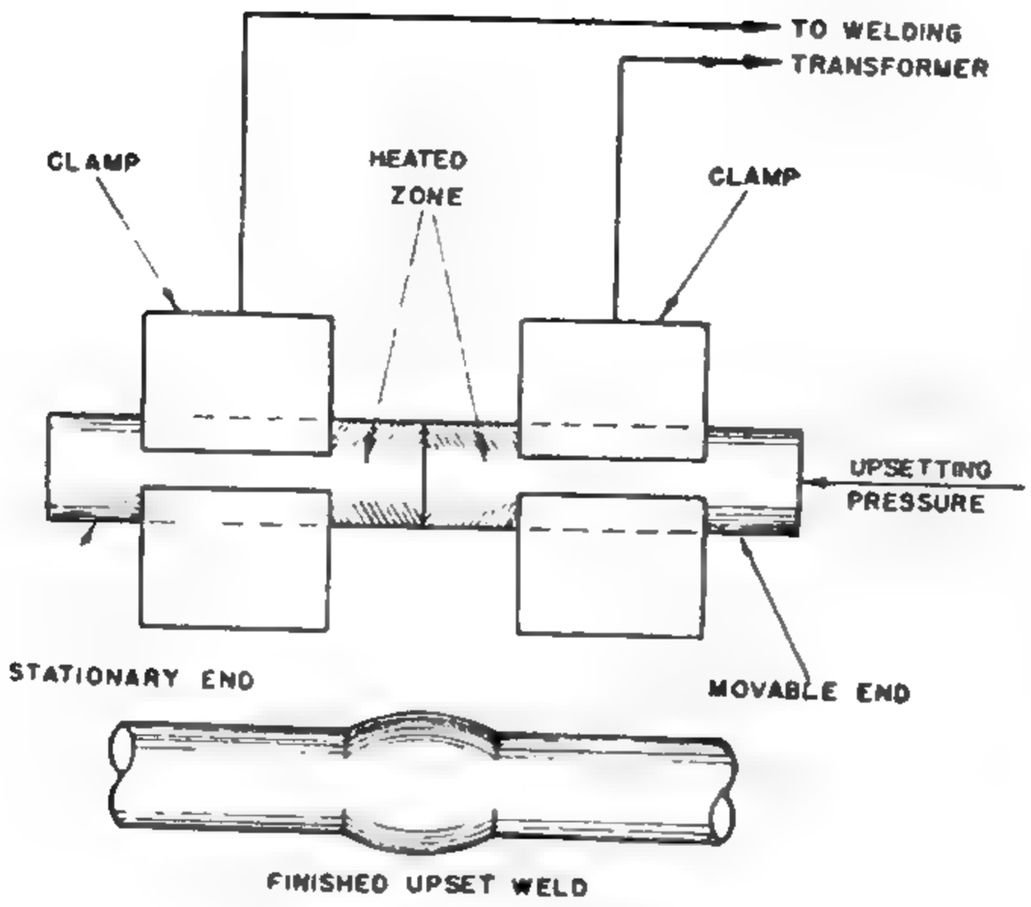


Fig. 15.—Elements of Upset Welding

The best results will usually be obtained if the parts to be upset welded are equal in sectional area and resistance. If the metals to be welded are similar in composition but of unequal areas, the part having the larger area should project out of the clamping die somewhat farther than the other piece. If the metals are of dissimilar compositions, the metal of higher electrical conductivity should project farther out of the die than the lower conductivity metal. To facilitate welding, the area of contact between the two parts to be welded is sometimes restricted by beveling the pieces at the abutting ends.

In the upset welding of large areas of pieces that do not make good contact with each other, it is sometimes the practice to interrupt the welding current periodically to allow heat to flow into the colder portions of the work, to prevent localized overheating and melting.

In the progressive upset welding of butt joints, such as the longitudinal joint in welded tubing or pipe, the formed tube passes through rolls and wheel electrodes which provide the pressure and welding current. The amount of upset is regulated by the position of the rolls or welding wheels, and the required welding heat is governed by the current passing through the work and the speed at which the tube goes through the rolls. Figure 16 (*a*) shows the steel strip entering the strip guide assembly and the first stages of the forming section. The heat regulator, located behind the forming section, can be adjusted either manually or by phase shift control. Figure 16 (*b*) shows the rotary-type, oil-cooled welding transformer with the control cabinet visible behind it. This welding equipment includes a dressing tool assembly for dressing the welding electrodes without removing them and a scarfing tool assembly which removes the upset metal after welding. As the third step the welded tube enters the straightening and sizing section, shown in Fig. 16 (*c*) after which it is cut to desired lengths. Other information concerning the equipment used for upset welding is contained in Chapter 15.

For upset welding, it is usually necessary to machine the weld surfaces on rolled stock, forgings and castings. Stampings are usually trimmed in the die but sometimes machined. In making upset welds, the welding surfaces must be clean and parallel and comparatively smooth, since otherwise the high spots may overheat and melt before the areas that are not in contact begin to heat.

C. PERCUSSION WELDING

FUNDAMENTALS OF PROCESS

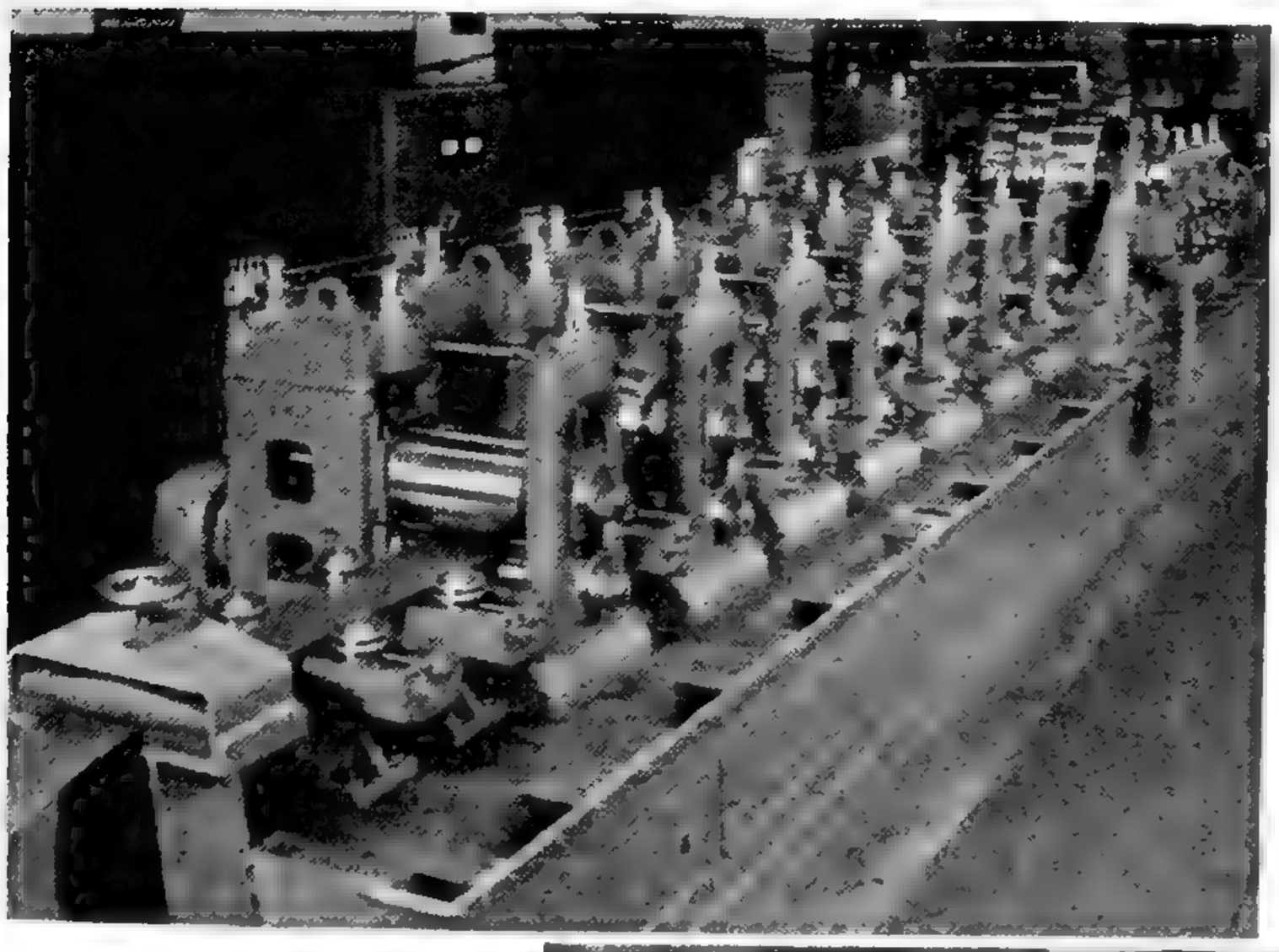
Definition and General Description

The term *percussive*, or *percussion welding*, has of late years been abused by applying it to certain types of welds made with very short timing. This is a mistake, however, because the principle of percussion welding is defined as "a resistance-welding process wherein coalescence is produced, simultaneously over the entire area of abutting surfaces, by the heat obtained from an arc produced by a rapid discharge of stored electrical energy, with pressure percussively applied during or immediately following the electrical discharge."

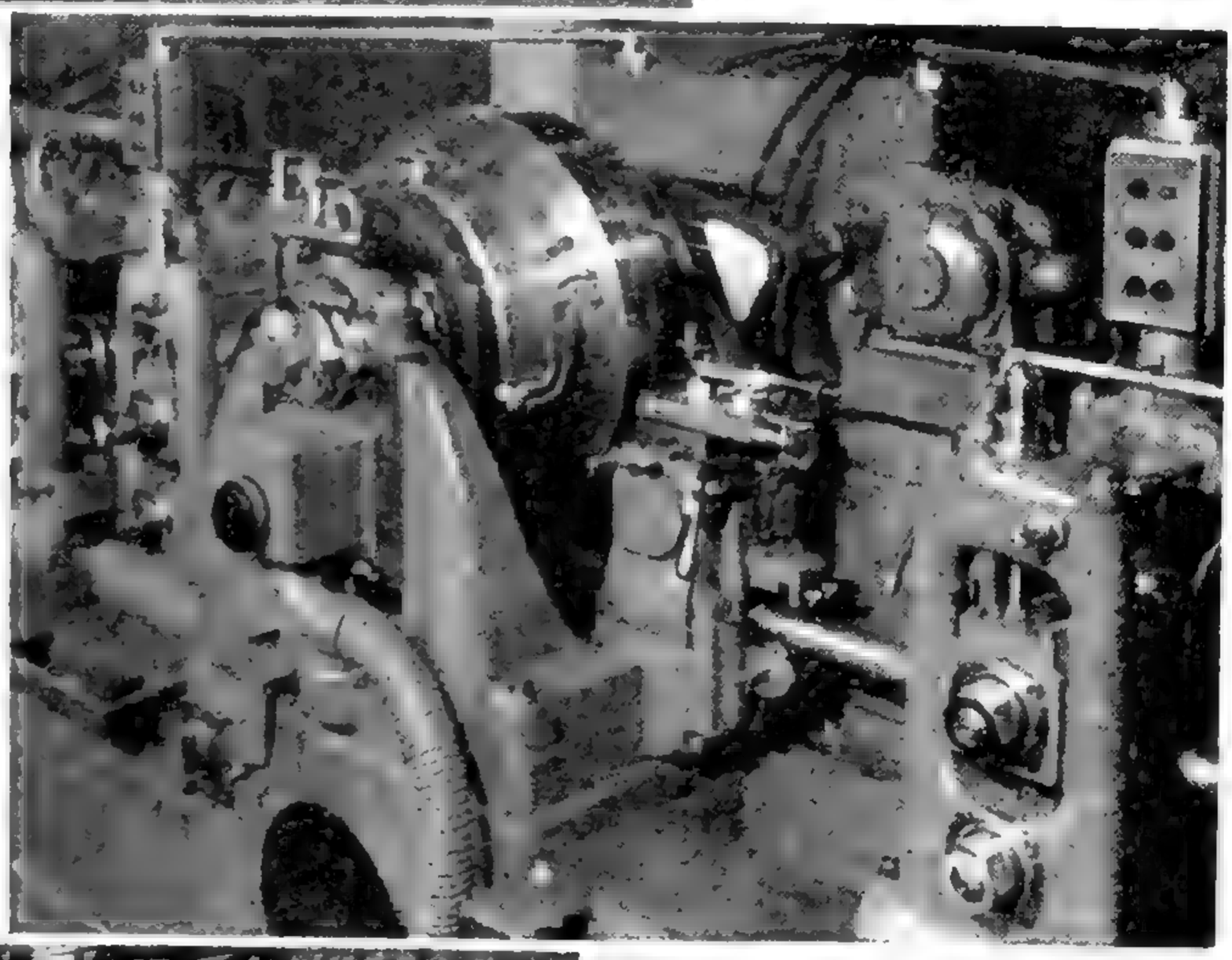
Since the only commercial applications of this process have been accomplished with the use of electrostatic capacitors, it must be considered as an electrostatic stored-energy system. It differs principally from the electrostatic system for spot welding in that no welding transformer is employed. Instead, the condenser discharge is applied directly to the weld. For a description of the equipment used in percussion welding see Chapter 15.

Principles of Operation

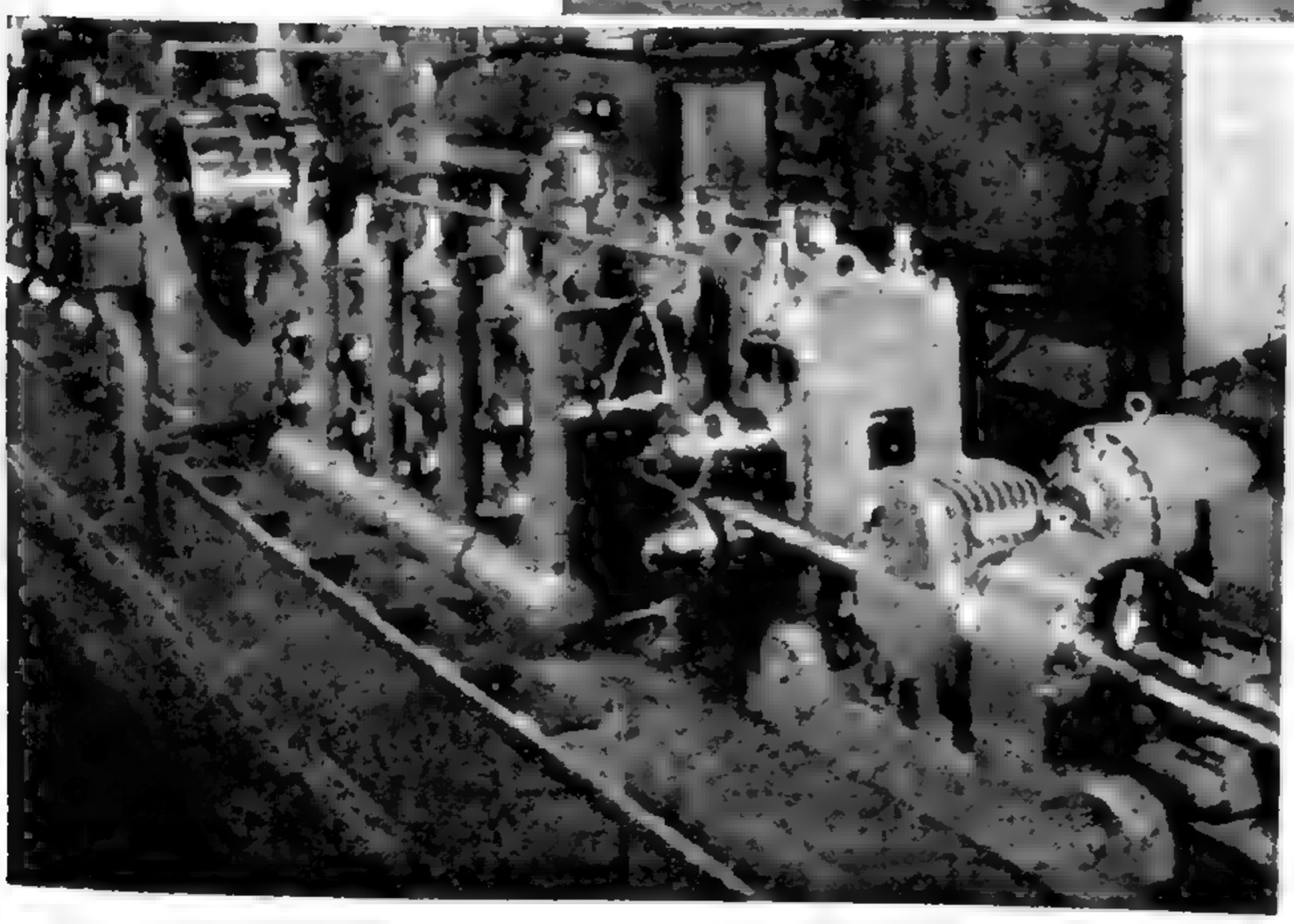
There are several variations of this process. The earliest method, as invented



(*a*) Steel strip entering the strip guide assembly and forming section.



(*b*) Rotary-type, oil-cooled welding transformer.



(*c*) Welded tube entering the straightening and sizing section

Fig. 16 —Tooling Used in Upset Welding Longitudinal Pipe or Tube Joints

by L. W. Chubb, utilized a low-voltage condenser connected to the two pieces to be welded and an electromechanical device for moving the pieces through the required pressure cycle. It was necessary in this process to first bring the work together; second, start the discharge of the condenser; third, draw apart the parts being welded practically simultaneously with the discharge of the condenser in order to create an arc between the parts and thus obtain a partial surface melting of the parts; and last, bring the parts together again with a heavy impact blow.

A subsequent improvement of this process made by Chubb replaced the condenser with an electromagnetic field, produced by sending direct current through the primary of a transformer. Upon interruption of the current, the collapsing field induced current in the secondary winding, which was connected to the parts to be welded. and started the same mechanical cycle of striking an arc between the parts welded by drawing them apart and then forcing them together with an impact force.

A third form of percussion welding, invented by F. C. Vang, consists in replacing the low-voltage condenser or electromagnetic field with a high-voltage condenser possessing sufficient potential to break across an appreciable air gap and thus obviate the necessity of first drawing apart the parts being welded in order to discharge the energy at the weld.

Figure 17 shows a simple sketch of the principle utilized by the Vang process. Condenser *C* charged to several thousand volts potential is directly connected to the parts being welded which are held apart by latch 1 against the force of a spring or an air piston. Upon the release of latch 1, the movable part is propelled toward the stationary part at a high rate of speed. When the air gap diminishes to about $^{1}/_{32}$ to $^{1}/_{16}$ in., depending on the condenser voltage, the gap breaks down, causing the condenser to discharge itself in this high frequency spark gap.

By judicious design of the electrical and mechanical characteristics of the circuit, a high-intensity arc can be produced of such short duration that its effect upon the parts being brought in contact is purely superficial—that is, only a surface layer of a few thousandths of an inch thickness on each part reaches molten state.

The Vang process, at present probably the most common form of percussion welding, has certain features not found in any other welding process.

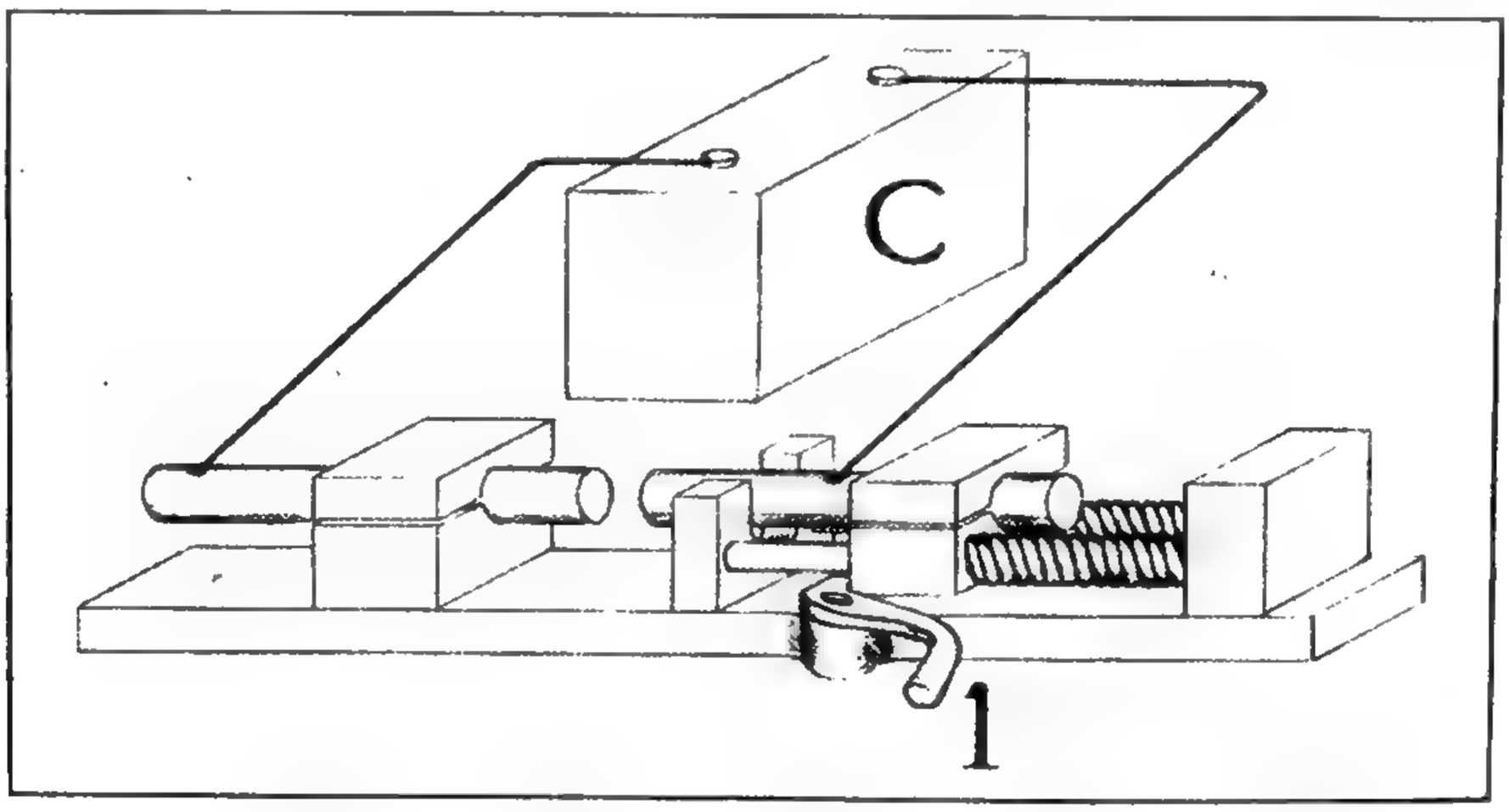


Fig. 17.—Schematic Sketch of Vang Method of Percussion Welding

To understand the operation of this process, it must be remembered that the duration of the arc is a matter of less than 0.001 sec., while the power expended in the arc is in the neighborhood of from 200 to 300 kilowatts. Because of this and of the fact that all of the weld energy comes from this arc, the electrical resistance of the parts to be welded does not affect the amount of heat generated at the weld and substances of entirely dissimilar characteristics can be readily welded as, for instance, stainless steel

to aluminum or copper. In fact, it makes no difference what either the electrical resistivity or the melting temperature of the part joined is as long as it is a reasonably good conductor of electricity. Further, the extreme brevity of the arc confines fusion to the surfaces of the parts welded and results in almost complete absence of flash.

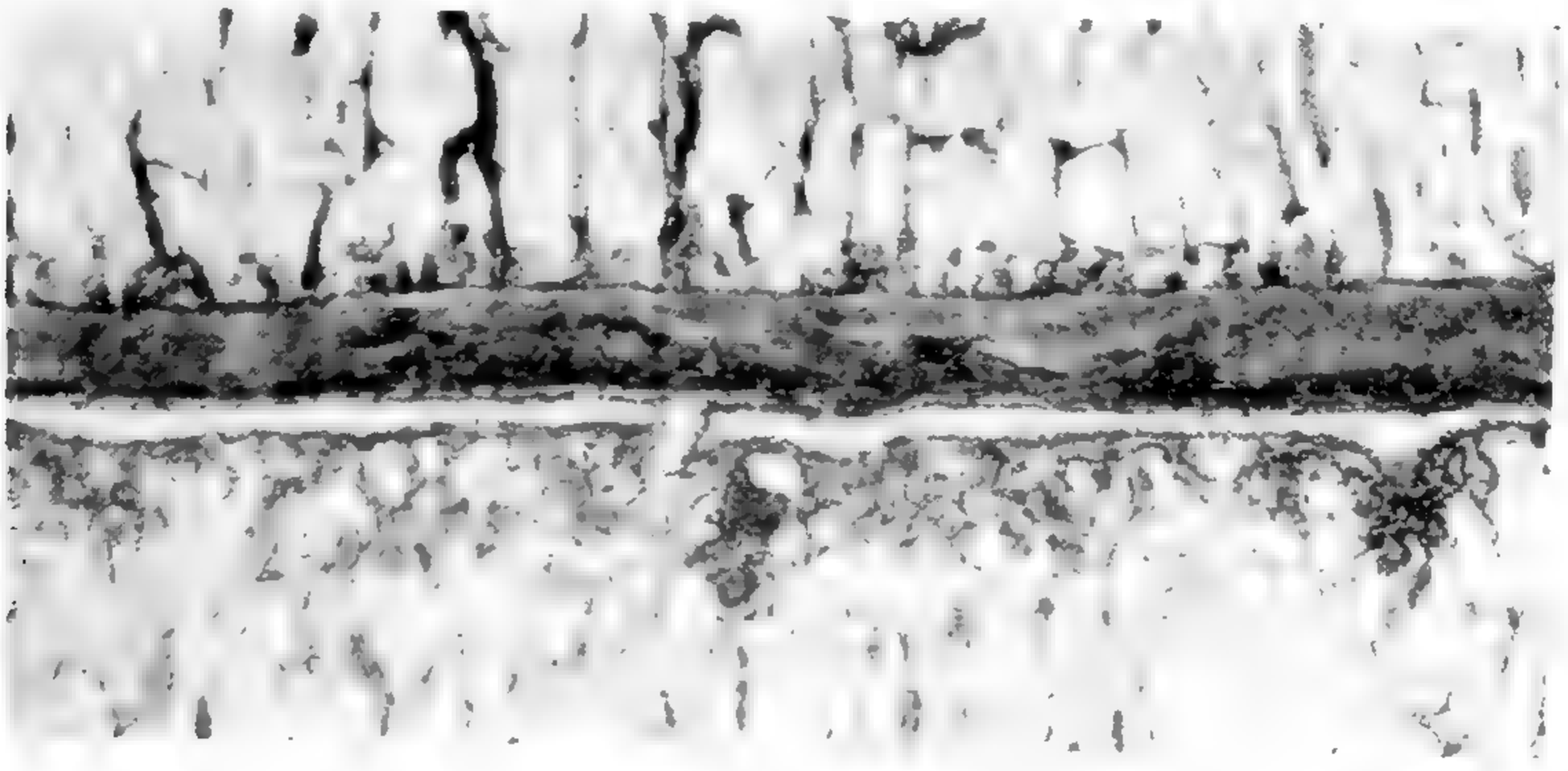


Fig. 18.—Percussion Weld Between Copper and Steel 250 ×

Figure 18 shows a photomicrograph of a copper to steel joint. The total thickness of weld and heat-affected zones is less than 0.010 inch. Figure 19 shows a destructive test made on a steel stud joined to a disk by this process.

EQUIPMENT USED

Although descriptive references have been made in discussing the fundamentals of this process, additional information concerning the machines, controls and auxiliary equipment used may be found in Chapter 15.

COMMON APPLICATIONS

Since the total depth of the heat-affected zone is of the order of 0.010 in., heat-treated metals such as hardened steel, cold worked stainless steel, etc., can be

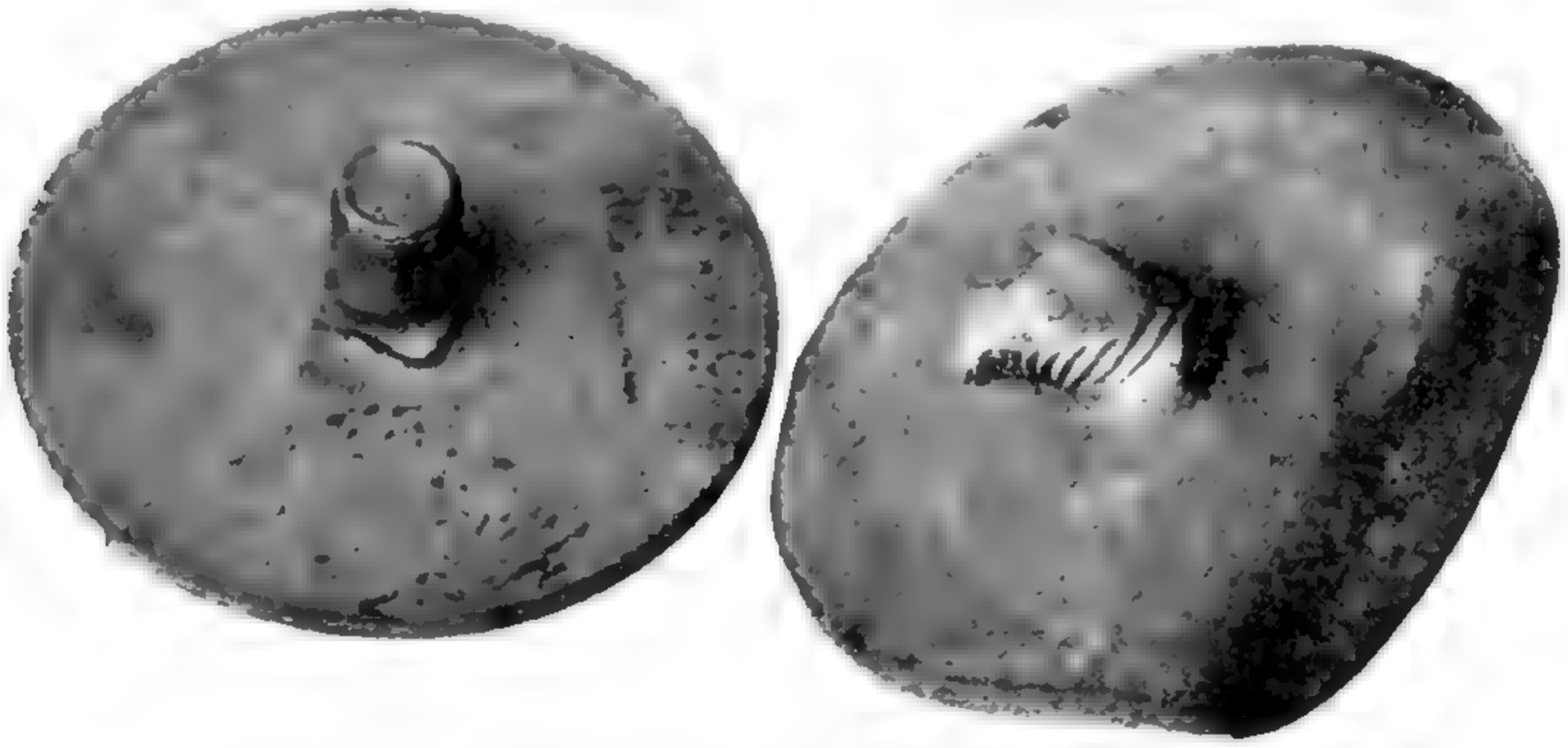


Fig. 19.—Percussion-Welded Stud Tested to Destruction

welded without annealing or otherwise destroying the heat treatment. For example, stellite tips can be joined to bronze valve stems and to stainless steel valve stems, and silver-graphite contact tips to copper stems by percussion welding. Since the heat-affected zone is only about 0.010 in. deep, it follows that the abutting surfaces must be accurately finished, and parallel with one another.

It must be remembered that all percussive processes are confined to butt-

welded joints. In addition, since control of the path of any arc is difficult, the total area that can be joined at any one time is limited for best results to not over $^1/_2$ sq. in., and then only when it is reasonably concentrated. It has been found that on larger sections the arc fails to distribute itself uniformly over the entire area and cold or unwelded spots result in parts of the joint.

In general it can be said that the process is suitable for joining pieces of rod, tube or pipe either to each other or to flat surfaces. Since this may be accomplished more economically by the flash-welding process, percussion welding is further confined to joining parts of completely dissimilar metals not normally considered weldable by flash welding, or of parts where complete lack of flash is imperative.

An additional and rather obvious limitation of this process is that the parts to be joined must be separate, that is, a ring or a band cannot be formed by joining the two ends together.

BIBLIOGRAPHY

1. *High-Speed Motion Pictures of Resistance Flash Welding,* W. E. Crawford and W. Richter, The Welding Journal, October 1936.

2. *Loss of Material in Flash Welding and Automatic Flash Welders,* E. Reitsch, The Welding Journal, July 1937.

3. *Temperature Distribution in Flash Welding,* H. Kilger, The Welding Journal Res. Suppl., January 1939.

4. *Flash Welding Alloy Steel Tubes,* W. Denker, The Welding Journal, June 1939.

5. *Resistance Flash Welding of Strip in Steel Mills,* J. H. Cooper, The Welding Journal, October 1940.

6. *Flash Welding,* L. A. Ferney, The Welding Journal Res. Suppl., August 1943.

7. *The Application of Flash Welding in Airplane Construction,* C. D. Smith, The Welding Journal, October 1943.

8. *The Flash Welding of Nickel and High Nickel Alloy Rod,* W. F. Hess and Albert Muller, The Welding Journal Res. Suppl., October 1943.

9. *Flash-Butt Welding—Welding Technique and Variables in Welding Low-Alloy Steel,* J. J. Riley, The Welding Journal Res. Suppl., January 1945.

10. *Flash Welding of Alloy Steels—Physical and Metallurgical Characteristics,* J. C. Barrett, The Welding Journal Res. Suppl., January 1945.

11. *Fatigue Properties of Flash Welds,* H. J. Grover, R. W. Bennett and G. M. Foley, The Welding Journal Res. Suppl., November 1945.

12. *Recommended Practices for Automotive Flash-Butt Welding,* American Welding Society, 1946.

13. *Production Technique and Quality of Flash-Welded Joints,* H. Kilger, American Welding Society, 1946.

14. *The Flash Welding of High-Drawn, High-Carbon Steel Wire,* R. D. Williams and R. W. Bennett, The Welding Journal Res. Suppl., October 1946.

15. *Flash Welding of Concentrated Areas Up to 24 Sq. In. in SAE 1020, NE 9440 and NE 8620 Steels,* D. Bruce Johnston, The Welding Journal Res. Suppl., February 1947.

16. *Resistance Welding Manual,* Resistance Welders Manufacturers Assn., Revised Edition. 1948.

CHAPTER 18

FORGE WELDING*

Definition and General Description

FORGE WELDING comprises a group of processes wherein the parts to be welded are brought to suitable temperature by means of external heating and the weld is completed by pressure or blows. The processes grouped under forge welding are hammer welding, die welding and roll welding.

In all of the forge-welding processes the parts to be welded are brought to a welding temperature by means of a furnace. In hammer welding this is accomplished frequently by placing a furnace over the work.

Pressure is applied after the parts have been properly heated. The essential difference between the three forge-welding processes is in the manner in which the pressure is applied. In hammer welding it is by blows of a hand or machine hammer; in die welding it is either by means of a bell or a mandrel and tube rolls; for roll welding it is by means of plate rolls.

The materials most commonly joined by forge welding are wrought iron which can be obtained in the form of bars, rounds, pipe, tubing, sheets and plates, and low-carbon steel (carbon content not exceeding 0.20%) which is similarly available in various forms.

When wrought iron and steel are heated to high temperatures, such as used in welding, and are exposed to the air, they oxidize rapidly. To secure a good bond between two pieces, this oxide must be so fluid that it is squeezed out from between the surfaces.

Clean silica sand and borax are two common fluxes used in forge welding. Borax, having a comparatively low fusion point, is used on high-carbon steel. It can be placed on the steel at low temperatures, after chamfering, consequently supplying a protective coating, or sprinkled on the steel while heating. It serves a double purpose, lowering the melting point of the oxide, and preventing further oxidation.

Silica sand is cheaper than borax and can be used on the low-carbon steels. Sand has a high melting temperature, but when combined with iron oxide it becomes fusible at lower temperatures. It is generally sprinkled on the metal when the welding temperature is approached.

Fluxes are not necessary in forge welding of wrought iron and very low-carbon steel, because it is possible to melt the oxide without burning or melting the metal.

Hammer welding is one of the oldest of the known welding processes. During the era of wagon travel and horse-drawn vehicles, blacksmith shops using hammer welding were in universal use. Now, however, there are few of these shops to be found. For most industrial purposes hammer welding has been replaced generally by other welding processes. The process is still used in a number of hardware and metal manufacturing applications; in the railway field, it is still largely used for safe ending or piecing boiler flues.

The most common current application of the roll-welding process is in the cladding of steel, described in Chapter 37A.

The most common current application of die welding is in the fabrication of pipe. This is described in Chapter 56.

More complete information on the application of forge welding will be found in the references listed in the Bibliography.

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* Prepared by the Handbook Committee.

BIBLIOGRAPHY

1. *Welding,* James Cran, Machinery, December 1908.
2. *The Welding of Metals and Liquid Fuels,* Journal ASME, June 1914.
3. *The Welding of Iron and Steel,* W. H. Cathcart, Iron Age, December 26, 1918.
4. For specifications covering material suitable for Forge Welding operations consult Index to Proceedings of ASTM, 1919–32.
5. *Chain, Cable and Some of Its Physical Properties,* C. G. Lutts, Proc. ASTM, 1920—II.
6. *Welding; Particularly Hammer Welding,* E. E. Thum, Chemical and Metallurgical Engineering, September 21, 1921.
7. *Steel for Forge Welding,* F. N. Speller, Mechanical Engineering, July 1922.
8. *Making Large Size Hammer-Welded Pipe,* G. F. Tagen, Iron Age, November 13, 1924.
9. *Welding of Iron and Steel,* C. A. Adams, Iron Age, October 28, 1926.
10. *Forging by the Blacksmith,* ASM Metals Handbook, 1939.

CHAPTER 19

THERMIT WELDING*

FUNDAMENTALS OF PROCESSES

Definition

THERMIT WELDING comprises a group of welding processes wherein coalescence is produced by heating with superheated liquid metal and slag resulting from a chemical reaction between a metal oxide and aluminum, with or without the application of pressure. Filler metal, when used, is obtained from the liquid metal.

Nature Of Thermit And The Thermit Reaction

Basic thermit is a mechanical mixture of finely divided aluminum and iron oxide in the form of magnetic iron scale. The proportions are, roughly, three parts of iron scale to one of aluminum. This mixture reacts according to the chemical formula:

$$8Al + 3Fe_3O_4 = 9Fe + 4Al_2O_3$$

The temperature resulting from the reaction is computed to be more than 5000° F. Due to the chilling effect of the crucible, however, the temperature of the liquid steel as poured into the mold for welding is slightly lower and has been measured at approximately 4500° F.

The reaction is non-explosive and relatively slow, requiring about 30 seconds. No hazard is incurred in handling or storing the mixture as an initial temperature of 2000 to 2100° F. is needed for ignition. To start the reaction, a special ignition powder, called *starting thermit*, is employed.

Actual thermit mixtures used for welding contain materials other than aluminum and iron oxide. In preparing such mixtures many variables, controlling both the time and the temperature of the reactions as well as the chemical analyses of the resultant weld metals, must be considered. For example, through the addition of metallic elements, either by means of metallic pieces which are melted during the reaction, or in the form of combinations of oxides of elements with aluminum, a wide variation in the analysis of thermit steel is provided. By the same means the tensile strength, ductility and hardness of the resultant steel are also controlled. For example, the tensile strength may be varied from 50,000 up to 110,000 psi., with corresponding elongations in 2 in. of over 40% to almost zero.

Principles Of Operation

In the pressure-welding process no weld metal is deposited and only the heat of the metal and the slag resulting from the reaction are utilized. The parts to be welded are butted tightly together and enclosed in a removable mold which provides a space between the inner surface of the mold and the parts. The products of the reaction are then poured into the mold in such a manner that the slag enters the mold first. The slag cools rapidly on contact with the metal parts and provides a layer of brittle glass-like material so that the thermit steel which follows does not fuse with or adhere to the surface of the parts. The thermit steel generally lies in the lower half of the mold with the alumina or slag in the upper half and both give up their heat to the pieces being welded. The steel and slag are allowed to remain until the ends of the pieces reach a welding heat, whereupon the pieces are forced together by means of clamps to make the pressure butt weld. The mold is then removed and the thermit steel and slag knocked off from around the weld.

In the non-pressure thermit weld proc-

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* Prepared by a committee consisting of J. B. Tinnon, Metal and Thermit Corp., *Chairman;* J. H. Deppeler, Consulting Engineer; Merritt Smith, Metal and Thermit Corp.

ess, which is more widely employed, the thermit steel is deposited as weld metal. This is the process used throughout industry for welding heavy sections of ferrous metals.

In making a weld by this process, the first step is the lining up of the parts and the cutting of a parallel-sided gap at a point where the weld is to be made, the width of the gap depending on the size of the section. Around the break or joint, a wax pattern is formed and a refractory sand mold is built which provides an annular space at the weld. The part is then preheated by means of kerosene and air blown into the mold through an opening. Preheating, which continues until the parts reach red heat, serves to burn out the wax of the pattern and to dry out the mold. Reaction is started by means of a small quantity of starting thermit placed on top of the thermit in a specially designed crucible. When the reaction is completed the crucible is tapped, allowing the thermit steel to run into the mold. This steel, having great superheat, and being held in place between and around the ends of the parts to be welded, gives up its superheat to these parts, fusing and solidifying with them upon cooling.

Characteristics Of Thermit Welds

A typical range of analyses of the steel produced by forging thermit and employed for welding is:

Element	%
Carbon	0.25—0.35
Manganese	0.40—0.60
Silicon	0.09—0.20
Sulfur	0.03—0.04
Phosphorus	0.04—0.05
Aluminum	0.07—0.18

A thermit weld of this composition has an average tensile strength of about 72,000 psi., with a yield strength of about 36,000 psi. In fact, although thermit weld metal resembles a cast steel, it actually has physical properties closely approaching those of forged steel.

Since thermit steels are produced through the reduction of extremely pure iron oxide by an almost perfectly pure aluminum they possess these physical properties as cast. Ordinary cast steels are produced from pig iron and other impure materials. On solidifying, the impurities tend to gather along grain boundaries so that fractures in cast steel always occur along the grain boundaries within areas of impurity. The purity of the thermit ingredients, however, eliminates most of this grain boundary condition and fractures in thermit steel occur almost without exception through the grains.

Description Of Materials, Equipment And Methods Of Making Welds

Most commonly used thermits for welding ferrous metals are:

Plain Thermit—a mixture of finely divided aluminum and iron oxide which is the basis for all thermit mixtures.

Forging Thermit—which is plain thermit with the addition of ferro-manganese and mild steel punchings and is used in welding steel.

Cast-Iron Thermit—consisting of plain thermit with additions of ferro-silicon and mild steel punchings, used for welding cast iron.

Wabbler Thermit—consisting of plain thermit with manganese and carbon additions and designed to produce a hard wear-resistant machinable steel for building up worn wabbler ends of rolls and pinions in steel mills.

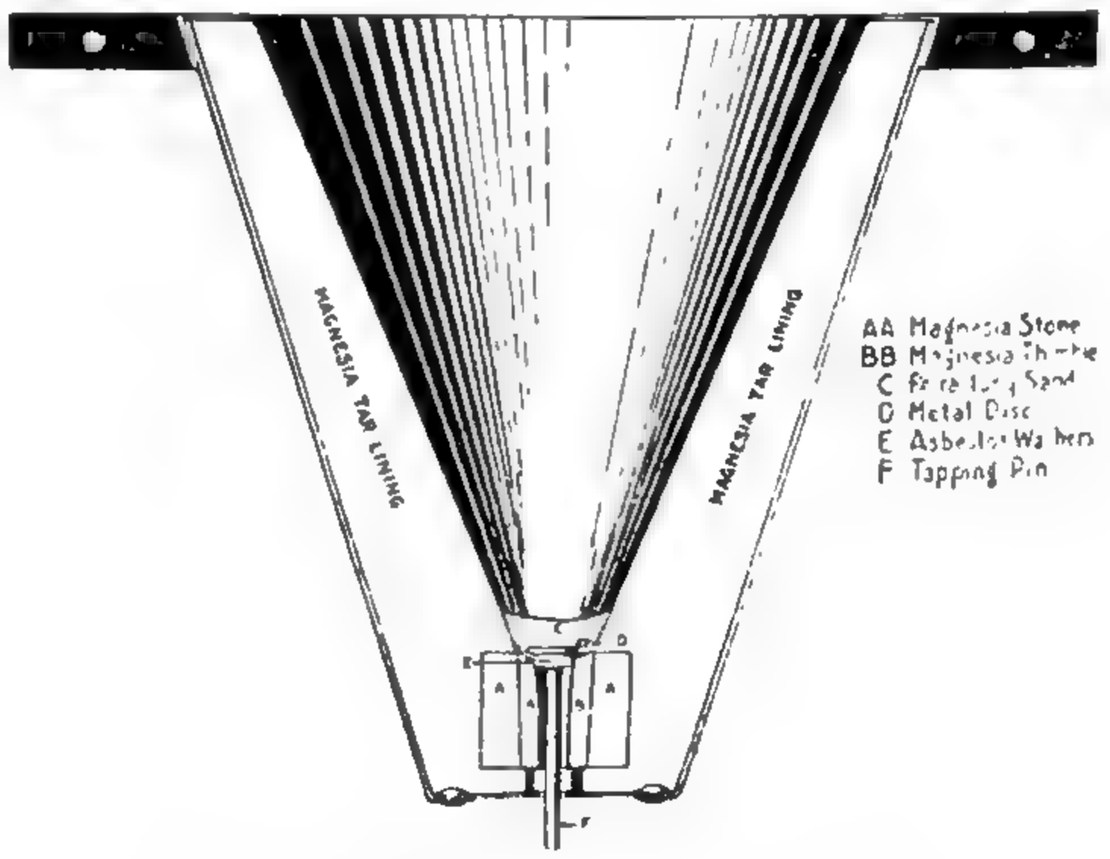

Fig. 1.—Thermit Automatic Crucible

Crucibles—The thermit reaction takes place in a magnesite-lined crucible (Fig. 1) which has at the bottom a hard, burned magnesite stone (*AA*). Into this stone a smaller magnesite stone or thimble (*BB*) is fitted, providing a channel through which the thermit steel may run. Before being inserted, the thimble (*BB*) is wrapped with one thickness of uncreased paper. The thimble is then inserted in the stone and plugged by sus-

pending the tapping pin (*F*) through the thimble and placing over it the asbestos washers (*E*) and the metal disc (*D*). The disc (*D*) is covered with refractory sand (*C*), the entire contents of the package furnished being used in each crucible.

Charging the Crucible.—Charging the crucible consists simply of placing in it the correct quantity of thermit. Before charging, however, it is important to mix the thermit thoroughly. Then a small quantity is placed gently on top of the plugging material before pouring the remainder into the crucible.

to preclude further use, crucibles may be completely relined.

Preheaters.—The regular thermit preheater (Fig. 2) operates with compressed air and kerosene. It is fitted with one or two burners, as desired, and with needle valves to give close regulation of the mixture of air and fuel so that good combustion may be obtained at all times.

For general work the double burner preheater is more satisfactory as it permits the use of one burner for preheating and the other for expanding. This is essential where one member of a double

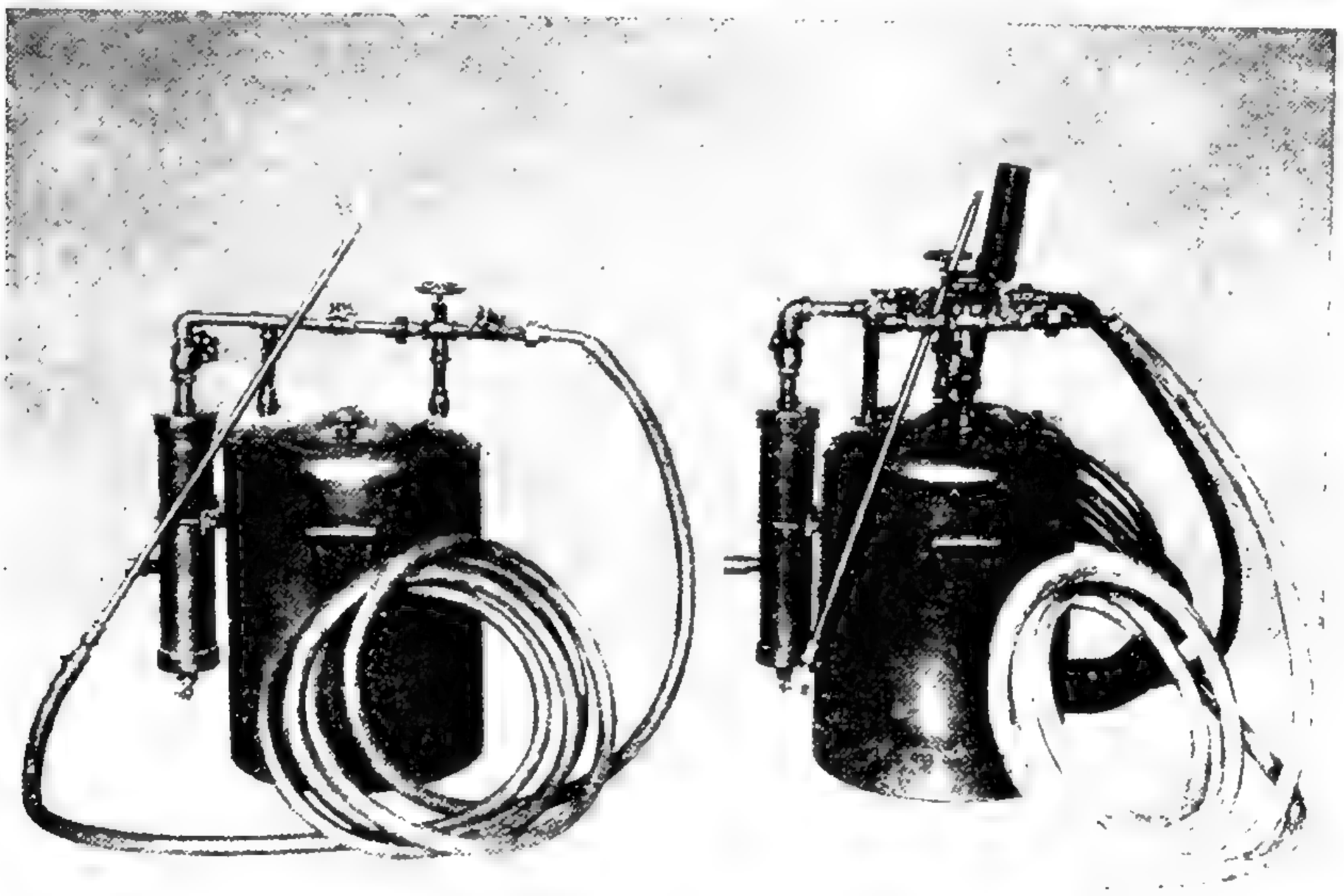

Fig. 2.—Single- and Double-Burner Preheaters, Showing Water Separators Attachment

Tapping the Crucible.—The crucible is tapped by knocking the tapping pin sharply upward into the crucible with a tapping spade or flat piece of iron approximately $1^1/_2$ in. × $^1/_4$ in. × 4 ft. long.

The thimble is removed by gently knocking it upward; a new thimble is used for each reaction. After crucibles have been used for several reactions, they may wear at the bottom and additional care must then be used in plugging to avoid self-tapping. Worn crucibles can be patched with magnesia tar to prolong their life. When linings are so far gone

bar frame is being welded, for while the parts to be welded are being preheated, the opposite member can be heated with the second burner and expanded to avoid residual shrinkage stresses when the weld cools. In large welds the two burners are required and operate through two heating gates.

The crucible and preheater comprise the only permanent pieces of apparatus required for thermit welding in general repair work. Details of various size crucibles are given in Table 1.

Molding Material.—It is highly important that proper molding material,

generally a mixture of high silica sand and plastic clay thoroughly mulled together, be used in thermit welding. The use of impure materials may result in blow-holes or glass-like inclusions in the weld metal. Material with poor binding qualities may cause breaking down of parts of the mold and result in burned base metal or lack of fusion between base metal and weld metal.

Making The Weld

Most thermit welds, whether in crankshafts, stern frames of ships or heavy steel mill rolls, are made in more or less the same general way. The following description, therefore, is for the purpose of covering a typical welding operation. The special features peculiar to particular applications are covered in the section headed applications.

Preparation of Joint.—To gage the allowance to be made for contraction of the weld as explained later on, it is desirable, after lining up the parts in preparation for cutting the gap, to place tram marks on the parts to be welded. These marks are made at points outside of the areas to be covered by the mold box. The metal may then be cut out along the line of fracture with an oxy-acetylene torch so that a straight-sided gap of from $^{3}/_{8}$ to $2\,^{3}/_{4}$ in. is provided. The amount of opening depends on the size of the section to be welded (see Tables 2 and 3).

Cleaning.—The sections must be thoroughly cleaned. All oxide and scale from the cutting operations, as well as all dirt and grease, must be removed as far back as the mold box extends. Then when the mold is rammed, there will be no grease to burn out during preheating which might leave a space between the mold and the parts to be welded.

Allowing for Contraction.—To make up for the contraction of the weld when it cools, the gap between parts is increased $^{1}/_{16}$ to $^{1}/_{4}$ in. depending on the size of the weld. In some cases, the increased space may be obtained by simply separating the parts and in other cases by forcing the sections apart with a jack or other mechanical means. In other cases, it will be necessary to expand by heating the member opposite to the section being welded. Under certain circumstances, in order to confine the heat or to preheat other parts, a small firebrick or sheet-iron furnace is built around the member being expanded. This, however, is done only at time of preheating. Care should be taken not to overheat for expansion, a black heat being sufficient.

In allowing for contraction of a thermit weld, the actual contraction of the small amount of thermit steel in the space between the pieces being welded is not the important factor. It must be remembered that during preheating the ends of the pieces at the fracture expand or approach each other by the amount of expansion of the adjacent parts from the heat absorbed. Actually, therefore, the contraction at the weld may vary from

Table 1—Details of Automatic Crucibles, Lining Materials, Cones, Stones, and Thimbles

Size of Crucible	Capacity In Pounds of Rod Mill Thermit	Outside Diameter at Top, Inches	Height, Inches	Size of Magnesite Stone for Relining	Size of Magnesite Thimbles To be Used	Size of Plugging Material To be Used	Weight of Magnesite Tar required for Relining, Pounds
No. 2	9	9½	9	No. 1	No. 1	No. 1	20
No. 2½	14	11	11½	No. 2	No. 2S	No. 1	35
No. 3	20	11½	13	No. 2	No. 2S	No. 1	44
No. CCP	23	13½	15½	Steel	No. 1	No. 0	46
No. 3P	24	12½	13½	No. 2	No. 2S	No. 1	50
No. 3SP	25	12½	11-5/8	Steel	No. 2S	No. 0	44
No. 3½	26 (1 Bag)	12½	14½	No. 2	No. 2S	No. 1	52
No. 4	32 "	13½	15½	No. 2	No. 2S	No. 1	59
No. 5	48 (2 Bags)	16½	16	No. 2	No. 2L	No. 2	90
No. 6	93 (3 Bags)	19	19½	No. 2	No. 2L	No. 2	152
No. 7	212 (8 Bags)	24	23½	No. 3	No. 3	No. 3	209
No. 8	274 (11 Bags)	26½	27	No. 3	No. 3	No. 3	243
No. 9	416 (16 Bags)	29	29	No. 3	No. 3	No. 3,	286
No, 10	530 (21 Bags)	32½	32½	No. 3	No. 3	No. 3	400
No. 12	984 (39 Bags)	38	36	No. 4	No. 4	No. 3	835
No. 15	1584 (63 Bags)	44½	42	No. 4	No. 4	No. 3	1145

1/16 to 1/4 in. Allowing for such contraction is, however, a comparatively simple matter. For example, if the fracture is opened up 1/4 in. to allow for contraction and if, during preheating, the parts approach each other almost 1/4 in. due to expansion of adjacent members, the parts being welded should be very nearly in line after welding. In welding large sections, relatively greater allowances are made for contraction than in smaller sections because preheating requires more time and consequently the heat is absorbed further along the parts causing greater expansion and an increased tendency to close up the gap at the fracture.

Wax Pattern.—The next step is the making of the wax pattern, which is formed around the parts to be welded in the exact shape of the collar of thermit steel desired in the finished weld. The opening between the ends of the parts is also filled with wax, as shown in Fig. 3. A vent hole, not shown in the drawings, is provided extending through the wax pattern from the preheating gate to the riser. A convenient way to do this is to imbed a 1/4-in. diameter cord in the wax. Pulling out the cord after the pattern has been formed leaves the required vent. The pattern is made of yellow wax warmed until plastic.

Molds.—The mold box is placed in position and securely blocked up so that all weight is removed from the sections being welded. Figure 4 shows the design of the mold box.

In ramming the mold a small amount of molding material is placed in the box and rammed hard, first around the edges and then in toward the center, the mold being kept level at all times. The material is packed as tightly as possible and care is taken that the parts underneath the pattern are all well rammed. The thickness of molding material from the edge of the collar need not be greater than the width of the collar and in many cases can be less except at the end of the mold where the pouring gate is located, and a thicker section may be necessary.

Gate Patterns.—The wooden heating gate pattern is set at the lowest point of the wax pattern and leading out to the front of the mold box where an opening is provided for it. Where sections to be welded are of the same size, this heating gate is centered directly on the wax pattern. If a light section is being welded to a heavy section, however, the preheating opening in the mold is directed more toward the heavy section in order to assure more uniform heating of the two sections. Molding material is then added and rammed to the level of the heating gate pattern.

With the heating gate provided for, another wooden gate pattern is set in a

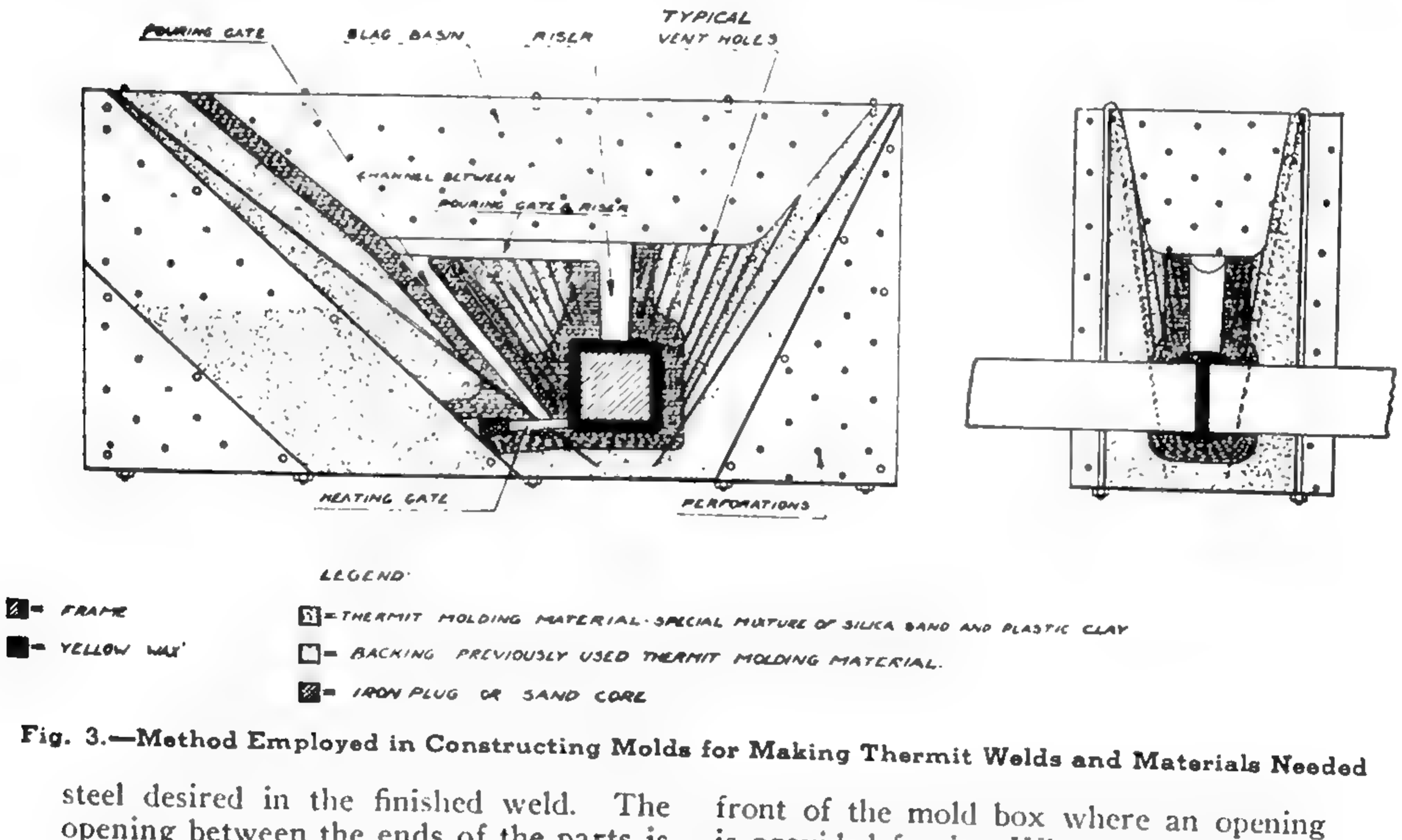

Fig. 3.—Method Employed in Constructing Molds for Making Thermit Welds and Materials Needed

Table 2—Thermit Weld Dimensions and Portions for Rectangular Sections

Section Width Height Inches	Gap Inches	Collar Inches	Riser Diameter Inches No.	Riser Diameter Inches Dia.	Pouring Gates No.	Pouring Gates Dia.	Heating Gates No.	Heating Gates Dia.	Connecting Gates No.	Connecting Gates Dia.	Thermit Required Pounds (x)	Section Width Height Inches
2x 2	7/16	1 1/2x7/16	1	3/4	1	3/4	1	1 1/4	—	—	6	2x 2
2x 4	9/16	1 5/16x9/16	1	3/4	1	1	1	1 1/4	—	—	12	2x 4
3x 3	9/16	2 1/16x9/16	1	1	1	1	1	1 1/4	—	—	12	3x 3
3x 6	11/16	2 3/4x11/16	1	1	1	1	1	1 1/4	—	—	25	3x 6
4x 4	11/16	2 5/8x11/16	1	1	1	1	1	1 1/4	—	—	25	4x 4
4x 8	7/8	3 7/16x7/8	1	1	1	1	2*	1 1/4	—	—	50	4x 8
5x 5	13/16	3 1/8x3/16	1	1	1	1	1	1 1/4	—	—	50	5x 5
5x 8	15/16	3 13/16x15/16	1	1	1	1 1/4	2*	1 1/4	—	—	75	5x 8
6x 6	15/16	3 5/8x15/16	1	1 1/4	1	1 1/4	2*	1 1/4	—	—	75	6x 6
6x 9	1 1/16	4 5/16x1 1/16	1	1 1/4	1	1 1/4	1	1 1/4	1	1 1/4	100	6x 9
7x 7	1	4 1/8x1	1	1 1/2	1	1 1/4	2*	1 1/4	—	—	100	7x 7
7x10	1 1/8	4 13/16x1 1/8	1	1 1/2	1	1 1/4	1	1 1/4	1	1 1/4	125	7x10
8x 8	1 1/8	4 5/8x1 1/8	1	1 3/4	1	1 1/4	2*	1 1/4	—	—	125	8x 8
8x12	1 1/4	5 1/2x1 1/4	1	1 3/4	1	1 1/4	1	1 1/4	1	1 1/4	175	8x12
9x 9	1 3/16	5 1/8x1 3/16	1	2	1	1 1/4	2*	1 1/4	—	—	150	9x 9
9x13	1 3/8	5 5/16x1 3/8	1	2	1	1 1/4	1	1 1/4	1	1 1/4	225	9x13
10x10	1 5/16	5 9/16x1 5/16	1	2 1/4	1	1 1/4	1	1 1/4	1	1 1/4	200	10x10
10x15	1 1/2	6 5/8x1 1/2	1	2 1/4	1	1 1/2	2*	1 1/4	—	—	325	10x15
11x11	1 3/8	6 1/16x1 3/8	1	2 1/4	1	1 1/2	2*	1 1/4	1	1 1/4	250	11x11
11x16	1 9/16	7 1/16x1 9/16	1	2 1/4	1	1 1/2	2*	1 1/2	1	1 1/2	400	11x16
12x12	1 7/16	6 1/2x1 7/16	1	2 1/2	1	1 1/2	2*	1 1/2	1	1 1/2	300	12x12
12x18	1 11/16	7 3/4x1 11/16	1	2 1/2	1	1 1/2	2*	1 1/2	1	1 1/2	500	12x18
13x13	1 9/16	7x1 9/16	1	2 1/2	1	1 1/2	2*	1 1/2	1	1 1/2	375	13x13
13x19	1 3/4	8 3/16x1 3/4	1	2 1/2	2	1 1/2	2	1 1/2	2	1 1/2	675	13x19
14x14	1 5/8	7 7/16x1 5/8	1	2 1/2	2	1 1/2	2	1 1/2	2	1 1/2	500	14x14
14x20	1 13/16	8 5/8x1 13/16	1	2 1/2	2	2	2	1 1/2	2	1 1/2	800	14x20
15x15	1 11/16	7 7/8x1 11/16	1	2 3/4	2	1 1/2	2	1 1/2	2	1 1/2	600	15x15
15x22	1 15/16	9 5/16x1 15/16	1	2 3/4	2	2	2	1 1/2	2	1 1/2	975	15x22
16x16	1 3/4	8 15/16x1 3/4	1	2 3/4	2	2	2	1 1/2	2	1 1/2	700	16x16
16x24	2	9 15/16x2	1	2 3/4	2	2	2	1 1/2	2	1 1/2	1150	16x24
18x18	1 15/16	9 3/16x1 15/16	2	2 1/4	2	2	2	2	2	2	950	18x18
18x26	2 3/16	10 13/16x2 3/16	2	2 1/4	2	2	2	2	2	2	1525	18x26
20x20	2 1/16	10 1/16x2 1/16	2	2 1/4	2	2	2	2	2	2	1225	20x20
20x30	2 5/16	12 1/16x2 5/16	2	2 1/4	2	2	2	2	2	2	2000	20x30
22x22	2 3/16	10 15/16x2 3/16	2	2 1/2	2	2	2	2	2	2	1550	22x22
22x32	2 1/2	12 7/8x2 1/2	2	2 1/2	2	2	2	2	4	2	2475	22x32
24x24	2 5/16	11 13/16x2 5/16	2	2 1/2	2	2	2	1 3/4	2	1 3/4	1875	24x24
24x36	2 5/8	14 1/8x2 5/8	2	2 1/2	2	2	2	2	4	2	3125	24x36
26x26	2 7/16	12 11/16x2 7/16	2	2 1/2	2	2	2	2	2	2	2275	26x26
26x38	2 3/4	14 15/16x2 3/4	2	2 1/2	2	2	2	2 1/4	4	2 1/4	3700	26x38
28x28	2 9/16	13 1/2x2 9/16	3	2 1/2	2	2	2	2	2	2	2775	28x28
28x42	2 15/16	16 1/8x2 15/16	3	2 1/2	2	2	2	2 1/2	4	2 1/2	4675	28x42
30x30	2 11/16	14 3/8x2 11/16	3	2 1/2	2	2	2	2 1/4	2	2 1/4	3275	30x30
30x45	3 1/16	17 3/16x3 1/16	3	2 1/2	2	2	2	2 1/2	4	2 1/2	5525	30x45

* Includes one separate back heating gate.

x Thermit required includes provision for a 10% excess of steel in slag basin for a single pour and a 20% excess for a double pour.

Formula upon which above table is based:—

$$\text{Gap} = \frac{\sqrt[3]{\text{Area}}}{3.6}$$

Thickness of collar at center = · Gap

Width of collar = $\frac{\sqrt[3]{\text{Area}}}{10}$ plus twice gap

In computing dimensions and Thermit required, the following were used:—

Length of riser = width of collar.

Volume of collar = 0.8 the rectangular volume of collar.

Long dimension of section always considered vertical.

POURING GATES AND RISERS NOT TAPERED

Table 3—Thermit Weld Dimensions and Portions for Round Sections

Diameter Inches	Gap Inches	Collar Inches	Riser Dia. Inches	Pouring Gates No.	Pouring Gates Dia.	Heating Gates No.	Heating Gates Dia.	Connecting Gates No.	Connecting Gates Dia.	Thermit Required Pounds (x)	Dia. Inches
2	7/16	1 3/8x7/16	3/4	1	3/4	1	1 1/4	—	—	5	2
3	9/16	1 7/8x9/16	1	1	1	1	1 1/4	—	—	11	3
4	5/8	2 3/8x5/8	1	1	1	1	1 1/4	—	—	25	4
5	3/4	2 13/16x3/4	1 1/4	1	1	1	1 1/4	—	—	25	5
6	7/8	3 5/16x7/8	1 1/4	1	1 1/4	1	1 1/4	—	—	50	6
7	15/16	3 3/4x15/16	1 1/4	1	1 1/4	1	1 1/4	—	—	75	7
8	1	4 3/16x1	1 1/2	1	1 1/4	1	1 1/4	—	—	75	8
9	1 1/8	4 5/8x1 1/8	1 1/2	1	1 1/2	1	1 1/2	—	—	125	9
10	1 3/16	5 1/16x1 3/16	1 1/2	1	1 1/2	2*	1 1/2	—	—	150	10
11	1 1/4	5 7/16x1 1/4	1 3/4	1	1 1/2	2*	1 1/2	—	—	175	11
12	1 5/16	5 7/8x1 5/16	1 3/4	1	1 1/2	1	1 1/2	1	1 1/2	200	12
13	1 7/16	6 5/16x1 7/16	1 3/4	1	1 1/2	1	1 1/2	1	1 1/2	250	13
14	1 1/2	6 11/16x1 1/2	1 3/4	1	1 1/2	1	1 1/2	1	1 1/2	300	14
15	1 9/16	7 1/8x1 9/16	2	1	1 1/2	1	1 1/2	1	1 1/2	350	15
16	1 5/8	7 1/2x1 5/8	2	1	1 1/2	1	1 1/2	1	1 1/2	425	16
18	1 3/4	8 5/16x1 3/4	2 1/4	1	2	1	2	1	2	575	18
20	1 7/8	9 1/8x1 7/8	2 1/2	1	2	1	2	1	2	750	20
22	2	9 7/8x2	2 3/4	2	2	2	2	2	2	1050	22
24	2 1/8	10 5/8x2 1/8	3	2	2	2	2	2	2	1325	24
26	2 1/4	11 7/16x2 1/4	3 1/4	2	2	2	2	2	2	1600	26
28	2 3/8	12 3/16x2 3/8	3 1/2	2	2	2	2	2	2	1925	28
30	2 1/2	12 15/16x2 1/2	3 1/2	2	2	2	2	2	2	2275	30

*Includes one separate back heating gate.

x Thermit required includes provision for a 10% excess of steel in slag basin for a single pour and a 20% excess for a double pour.

Formula upon which above table is based:—

$$\text{Gap} = \frac{3\sqrt{\text{Area}}}{3.6}$$

Thickness of collar at center = Gap.

$$\text{Width of collar} = \frac{3\sqrt{\text{Area}}}{10} \text{ plus twice gap}$$

In computing dimensions and Thermit required the following were used:—

Length of riser = width of collar.

Volume of collar = 0.8 the rectangular volume of collar.

POURING GATES AND RISERS NOT TAPERED.

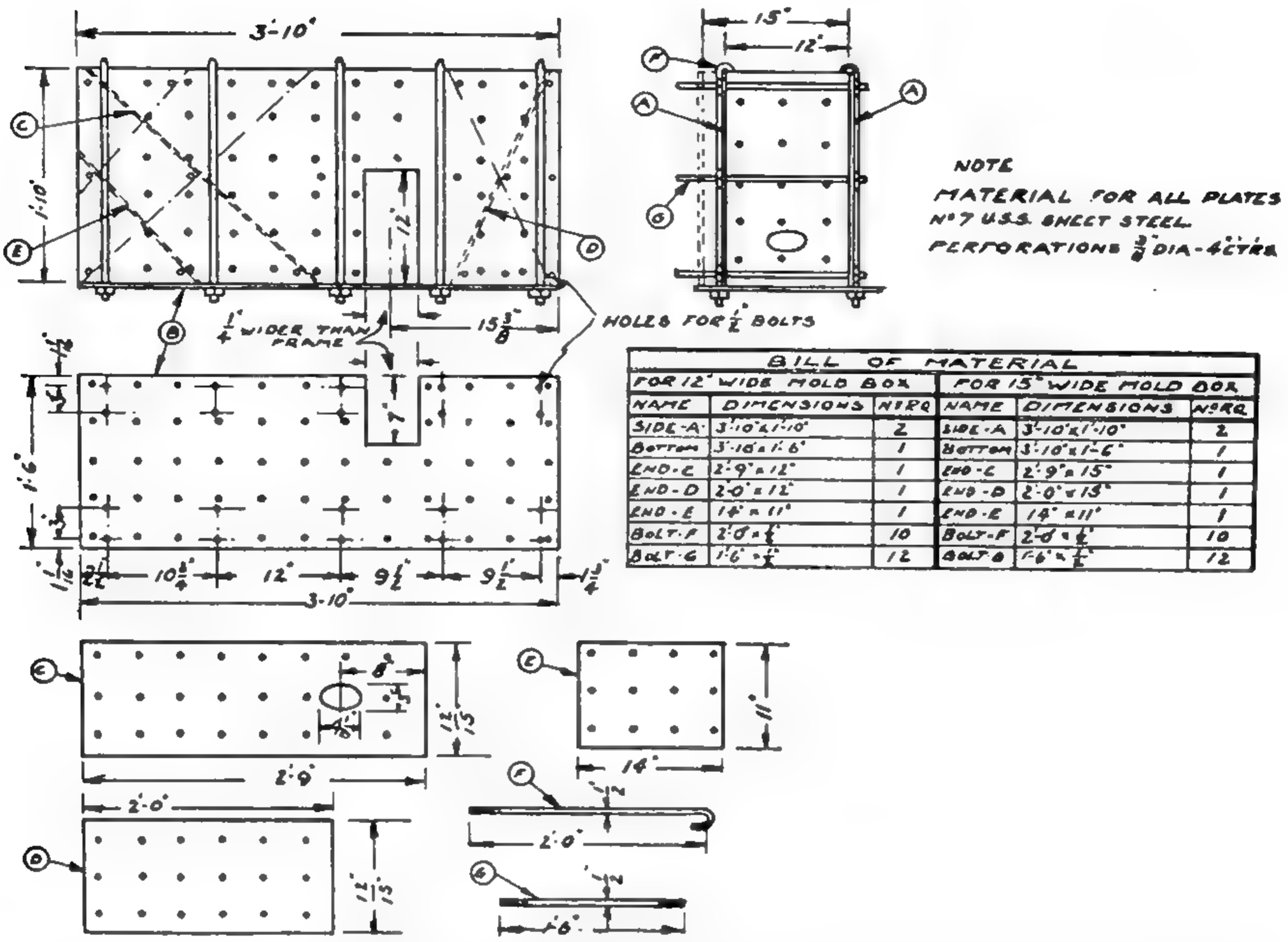

Fig. 4.—Design and Materials Required for Standard Mold Box in Making Thermit Welds on Sections up to 6½ x 8 In. in Size. Larger Mold Boxes Are in Proportion

vertical position directly above it and placed an inch away from the wax pattern to provide a pouring gate. Molding material is then added and rammed, a little at a time, until, except for the depression at the top which provides a slag basin, the mold box is filled. As a last step, molding material is troweled away from the top of the pouring gate to provide a larger opening and a shelf onto which the thermit steel may be tapped.

To prevent crumbling of the molding material under the blast of the preheating flame, it must be particularly well rammed around these patterns.

Drawings for various patterns are shown in Fig. 5.

Riser.—Following the ramming of the molding material around the heating and pouring gate patterns, a wooden riser pattern, as shown in Fig. 5, is placed at

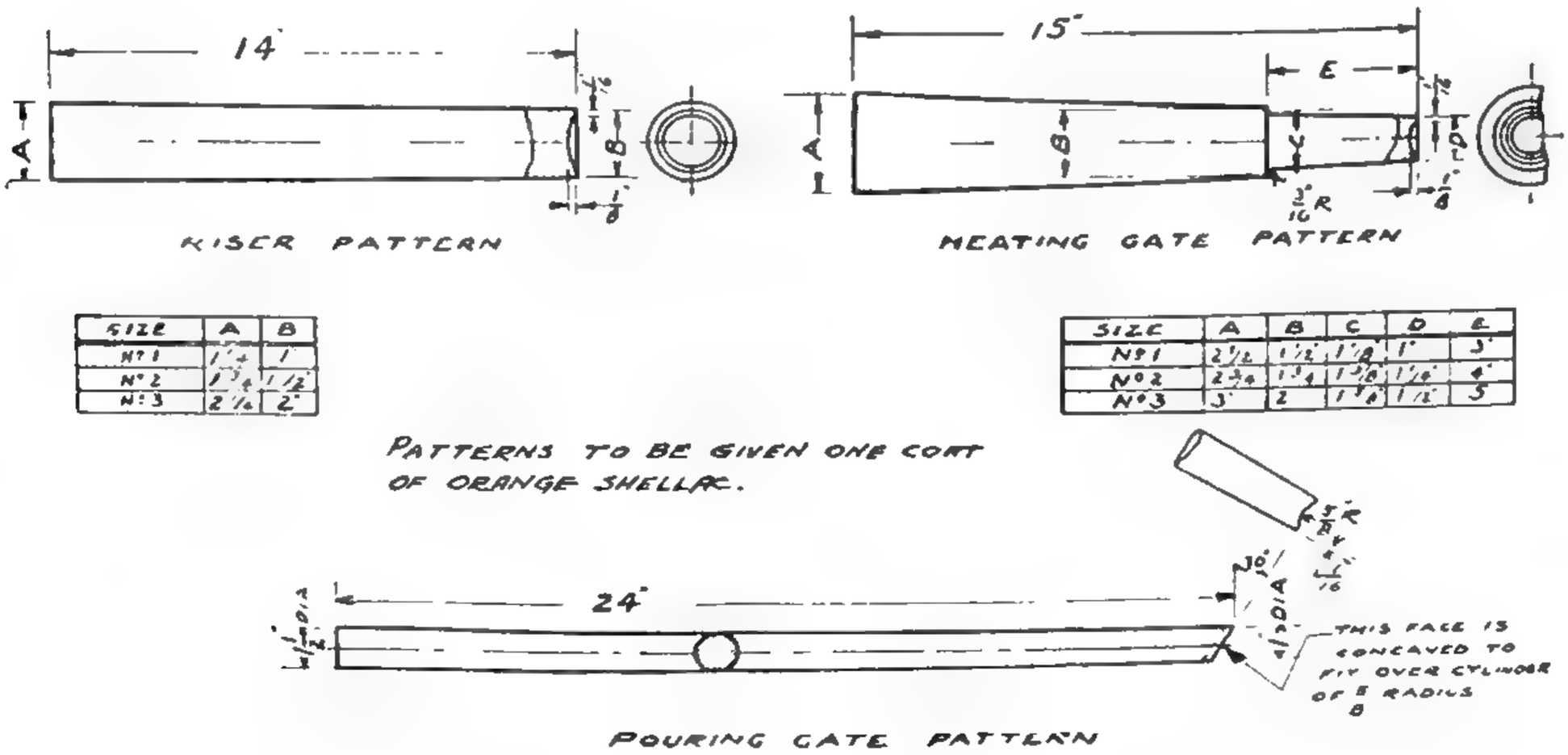

Fig. 5.—Wood Patterns for Pouring Gate, Riser and Heating Gate of Mold

the highest point of the wax pattern and the mold box is then rammed up solid. If there is more than one high point, a riser is required for each.

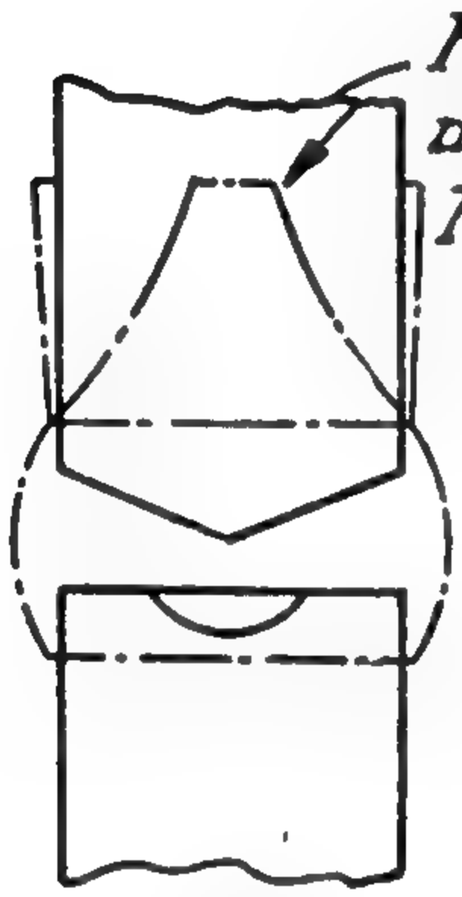

Fig. 6.—Design of Riser for Vertical Weld

Riser for Vertical Welds.—In case of a weld on a vertical member, provision for supplemental risers above the weld is made in order to provide vents and allow the thermit steel to fill the mold completely.

Supplemental risers for vertical welds may be made by applying wax $^{3}/_{16}$ in. thick on the upper section from the top of the wax collar pattern to the level of the top of the mold. This forms an efficient vent at the top of the collar, as well as providing the desired riser, and the resulting thin slab of thermit steel may be readily cut away after the weld is completed (Fig. 6).

Venting of Mold.—When the mold is completely rammed, the top is hollowed out to provide a catch basin for the slag, and a channel provided connecting the riser and pouring gate openings.

The next step is to vent the mold thoroughly with a vent rod made from 8- to 10-gage wire. Venting is an important factor in that it permits the escape of gases from the liquid metal. Vent holes to be useful should not reach the wax collar.

A typical mold with risers, gates and vents is shown diagrammatically in Fig. 3.

Completing Mold.—Wooden patterns for the various gates and risers are removed after tapping them gently to loosen them and any loose sand that may have fallen into the holes is removed with a molder's lifter. The openings are then covered so that nothing may fall into them and the crucible, which has been plugged in accordance with directions already given, is placed in position with the bottom about 10 in. above and over the shelf at the entrance of the pouring gate. Where the crucible cannot be so placed, a runner is constructed of molding material to lead the liquid steel into the mold.

Preheating.—Preheating is done with the usual thermit preheating equipment which blows finely atomized kerosene with compressed air into the heating gate, the mold acting as the combustion chamber.

Fig. 7.—Crucible Provided with Extension Ring for Holding Additional Quantity of Thermit

In starting the preheating operation, the burner of the preheater is set to point into the heating gate but is placed about 1 in. away from the opening. The blast is applied gently at first to avoid cutting the mold while it is still damp. The wax pattern burns away, leaving a perfect mold the exact shape of the desired weld. Heating is continued until the mold is thoroughly dry and parts to be welded attain a good workable heat. Regulation of the flame is accomplished by reducing or increasing the air pressure so as to

make the hotter part of the combustion chamber at the lower portion or the upper portion of the weld, as required.

Preheating is extremely important and must be thorough. To test the heat, the burner is removed for a period of 1 to 4 min., depending on the size of the weld, and if parts are still red and no dark spots appear, it is safe to assume that sufficient heat has been absorbed.

Charging the Crucible.—While preheating is in progress, the crucible which previously has been plugged, may be charged, as already outlined. No starting thermit should be added until it is time to ignite the thermit. If the thermit charge comes higher in the crucible than 2 in. from the top or if it is necessary to tip the crucible, a ring, as shown in Fig. 7, is added to give more height to the crucible. This ring should be sufficiently smaller than the crucibles in diameter to permit its being set down into the crucible at least 1 inch. Such a ring is generally 8 to 24 in. high and requires luting with fire clay.

Plugging Heating Gate.—When the sections to be welded have attained proper heat, the covers over the openings are taken off, the preheater burner is quickly removed and directed down the riser for a moment or two, or down the pouring gate if the riser is inaccessible, in order to blow out any dirt or sand which may have fallen into the mold. The heating gate is plugged by pushing a dry sand core, a piece of fire brick shaped to fit, or an iron plug, into the heating gate until it meets the shoulder provided for the purpose, as shown in Fig. 8. This plug is backed by tamping molding material into the heating gate behind it.

Igniting Thermit.—The thermit is ignited by means of a special starting thermit. A small quantity of this powder

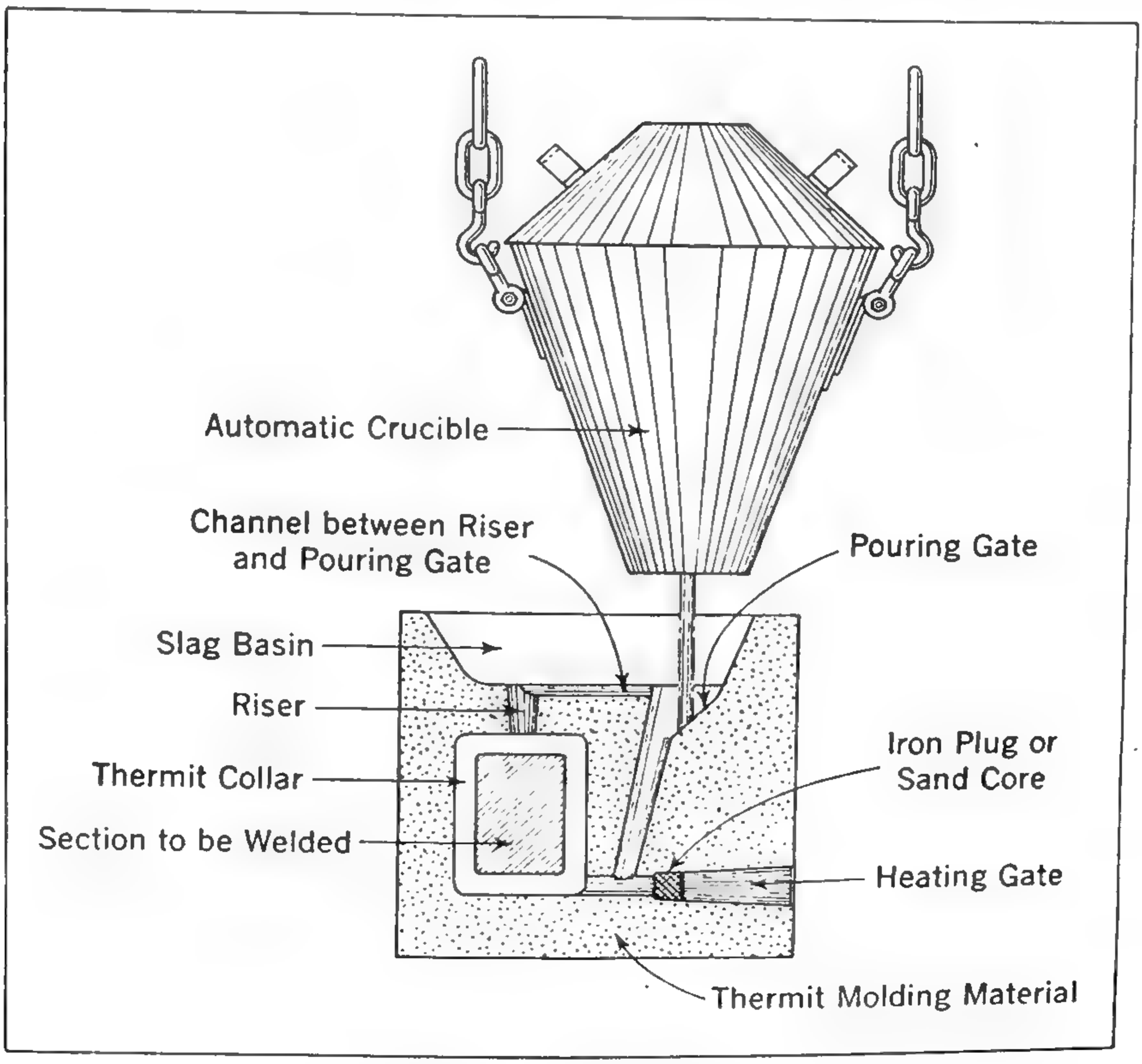

Fig. 8.—Method of Plugging Heating Gate

(half a teaspoonful is ample) is placed on top of the thermit in the crucible and the powder is touched off with a red hot rod or wire. When a large quantity of thermit is to be reacted, the starting thermit is poured in several criss-crossed lines on top of the thermit before igniting it. Reaction begins immediately and ample time must be allowed for its completion. Approximately 35 sec. after igniting the thermit, however, it is safe to tap the crucible as has been previously directed, permitting the contents of liquid steel to run into the mold, and the alumina slag to run into the basin provided for the purpose on top of the mold.

Cooling Precautions.—When contraction has been allowed for by jacking the pieces apart, the jack should be left in position until the thermit steel has cooled sufficiently to take this load. Likewise, if expansion has been obtained by heating a parallel member, heating should be continued until the weld begins to contract, when it can be stopped and the two parts allowed to cool together. The length of time that the jack or preheater burner may be left in place after making the weld depends largely on the size of the sections and the length of the preheating.

Annealing the Weld.—After the weld is made, the weld metal may be thoroughly annealed by allowing the mold to remain in place overnight, or for at least six hours.

Finishing the Weld.—After the mold is removed, the risers and gates are cut away with an oxy-acetylene torch, and, in the case of shafts or similar parts, the collar of thermit steel is machined off completely, if desired.

Quantity Of Thermit Required

The quantity of thermit required for welding sections of different sizes is shown in Tables 2 and 3.

Quantities may also be calculated, however, from the weights of the wax patterns. When the supply of wax is weighed before and after making the pattern, the difference gives the weight of the wax used in the pattern. Then for every pound of wax used, the steel from 25 lb. of thermit is required. When calculating by this method, it is, of course, essential that the entire space to be filled with thermit steel be filled with wax.

Calculating the quantity of thermit in advance of making a weld is also possible by estimating the total number of cubic inches of space to be filled with thermit steel and allowing three-quarters of a pound of thermit for each cubic inch. This allowance provides sufficient steel for welds, gates and risers.

COMMON APPLICATIONS

Thermit Welding is employed throughout industry for both fabrication and repair of heavy sections of ferrous metal such as those encountered in housings, frames, shafts and other parts of heavy machinery and equipment, including stern frames of ships. Thermit welding is also used in welding rails on street railways and steam railroads, in coal mines and on the runways of heavy cranes. In addition, it has been employed extensively by steel mills for the reclamation and emergency repair of broken rolls, pinions, and similar parts, as well as for the replacement of metal worn away in service on such parts as wabblers of rolls and pinions.

By incorporating simple forgings and small castings or oxygen-cut shapes thermit welded together into the design of heavy units, the cost of heavy pieces can often be reduced to a fraction of what it would be if large intricate castings were employed. The difficulties of obtaining sound metal where very large castings must be poured are eliminated. At the same time, many of the inherent delays of cast construction can be avoided and production can be effectively speeded. This is particularly true where changes in design are involved or entirely new units are to be built, since welded fabrication eliminates the costly, time-consuming work of making new patterns.

While many of these same advantages apply to welded fabrications involving other welding processes, where very heavy sections are involved, the thermit process may be the only practical method. In the first place, preparation of parts for thermit welding is simpler than that required with other welding methods and usually may be accomplished by flame cutting, eliminating the need for machining of intricate joint designs, always a slow, expensive operation. Also, time required for thermit welding, including the construction of molds and preheating, is

invariably much less than that needed to deposit weld metal layer by layer, by arc welding. As already explained, a properly made thermit weld has no high locked-in internal welding stresses and therefore stress relieving is unnecessary.

Crankshaft Repairs

In the repair of crankshafts and other shafts, including rudder stocks and cross heads, the important feature is the proper control of expansion, contraction and other factors which may lead to misalignment or defects after welding.

Alignment.—Such repairs may be made using supporting blocks (Fig. 9). The longer end of the shaft is clamped rigidly in place while the shorter end, left free to move in the line of the weld, is set at such a distance that when the weld cools and contracts, the short end of the shaft is drawn back into approximate alignment. In such work it is usual practice to substitute a new forging for the short end, slightly larger in size than the original end. After this new end is welded on, it is machined down to the proper diameter and any slight misalignment is automatically corrected.

Steel Mill Repairs

Welding Necks on Rolls and Pinions.—Where the neck is broken off a roll or pinion, it is generally more satisfactory, instead of welding the broken piece back on, to replace it with an entirely new piece. The new part, which is cast or forged slightly oversize, is welded on in the usual way and then machined to proper diameter and alignment.

Building up Worn Wabblers.—Where

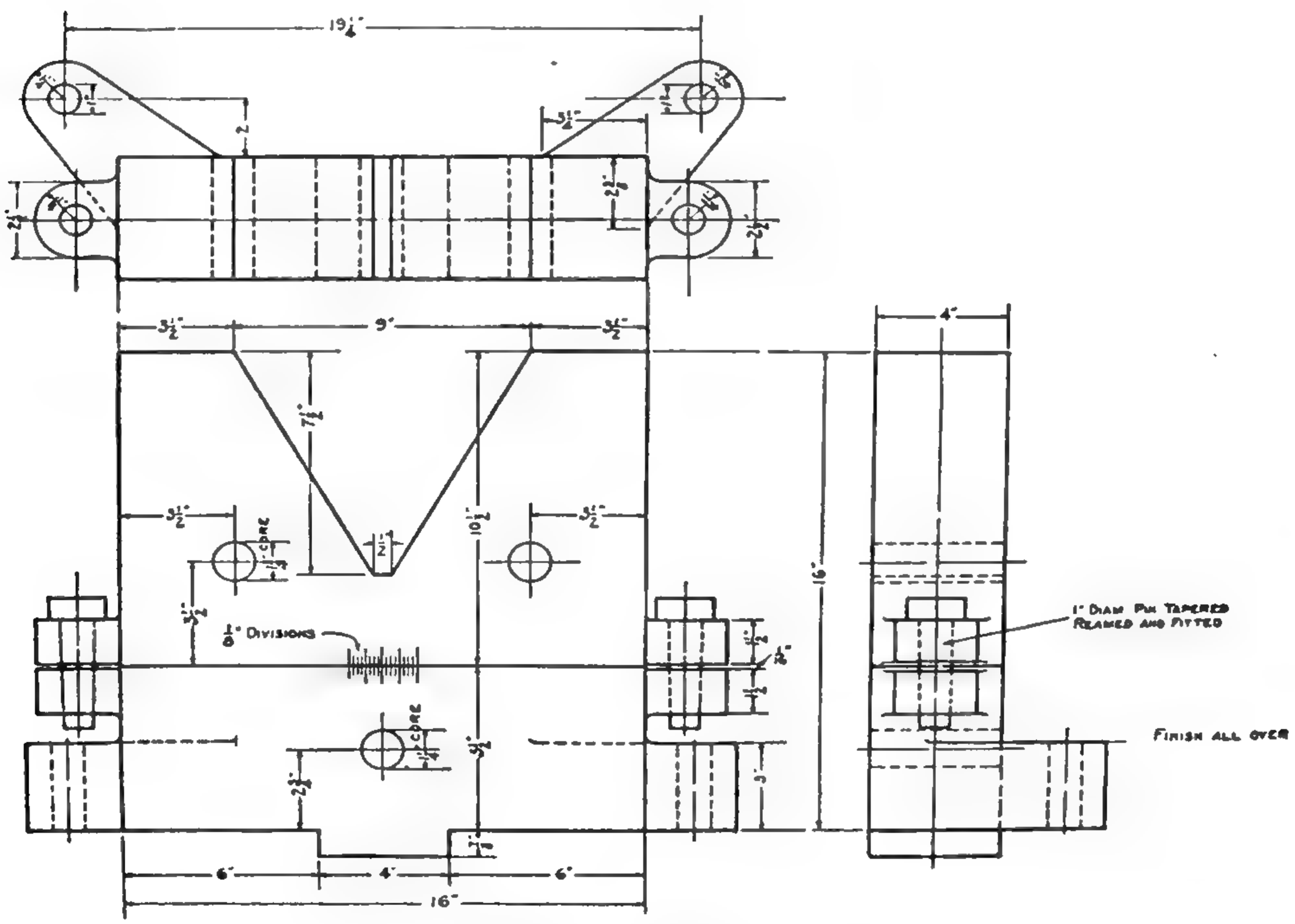

Fig. 9.—Proper Design of V-Blocks for Welding Crankshaft

wabblers are badly worn away or battered, it is best to cut away the worn section and weld on a new neck, as outlined above. If the wear is not too great, however, the worn parts may be satisfactorily rebuilt with thermit steel. Wabbler thermit, especially designed for this purpose, is used and the resulting deposited metal, while machinable, is sufficiently hard and

tough to provide longer wear than the original metal in the piece.

New Teeth in Large Pinions.—Repairs of this sort usually consist of replacing teeth, or parts of teeth, which have been broken or worn away. They represent a different problem from the ordinary weld in that the tooth is a comparatively small projection in an extremely heavy steel forging or casting. If repaired in the usual way, the heat would be carried away so quickly from the point at which the weld was being made, particularly during the interval of removing the preheater burner and tapping the crucible, that in many cases no weld would result. Everything possible, therefore, must be done to conserve the heat at the weld and it is usually necessary to heat the entire pinion to a red heat. This is done by bricking in the heavy parts and preheating with oil or gas burners, operated in conjunction with the regular preheater, while the preheating of the weld is under way. Care must be taken, however, to bring up the heat slowly, as there is some danger of cracking the pinion (Fig. 10).

Rail Welding

On Street Railways

The welding of street railway rails has proved one of the fields of greatest usefulness for thermit welding, having been standard practice for the past 30 years on most of the street railways in the United States. This process has eliminated rail joints, and effectively prolonged rail life and does away with joint maintenance.

In the welding of rails with thermit, the same general procedure is followed as in other work. Through simplification, such as the use of permanent patterns and other refinements, however, the process has been adapted to the making of quantities of identical welds on almost a production basis.

There are two methods by which thermit welds are made on street railway rail.

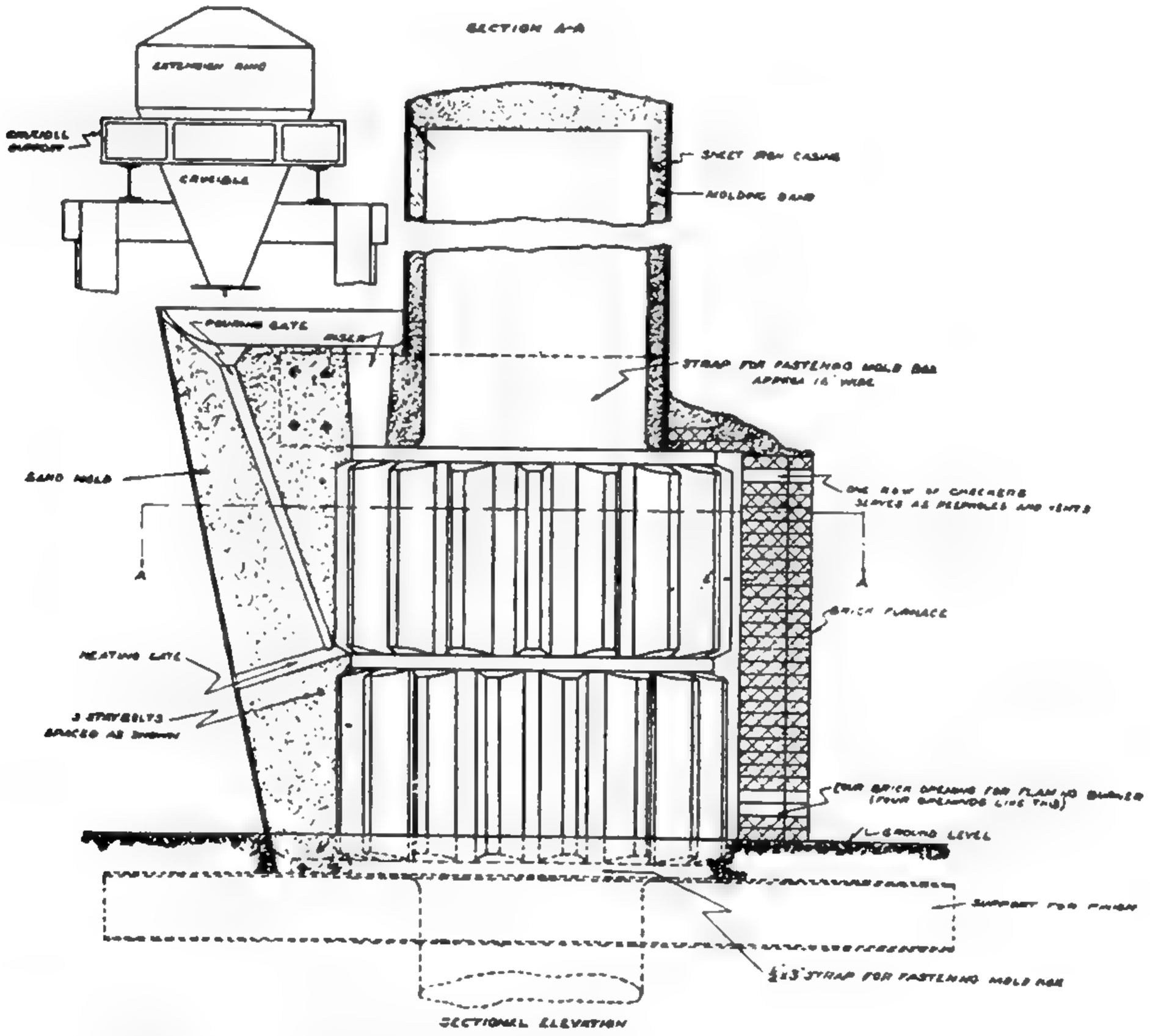

Fig. 10.—Method of Setting Up Mold Box and Brick Furnace in Pinion Tooth Welding

One is with the use of inserts while the other involves undercutting the rail ends.

Inserts.—In this method, an insert cut from a piece of rolled steel having the same analysis as the rail itself is placed between the rail heads at the running surface. The liquid thermit steel poured into the gap between the rail ends below the insert, fuses with the webs and bases of the rails and the bottom and rear surfaces of the insert, effecting a weld between these portions.

Simultaneously, the insert and the ends of the rail heads are brought to welding heat and the expansion of the rails from the intense heat of the weld, as well as the contraction of the thermit steel as it cools, causes the rail ends to exert tremendous pressure against the insert resulting in a butt weld of rail heads and insert.

Undercutting.—Where undercutting is employed, no inserts are used but rail heads are butted tightly together and a gap is cut in the webs, bases and lips of the rails at the joint to provide space for deposition of the weld. The overhanging portions of the rail heads actually form an attached insert and are welded in much the same way as when a separate insert is used.

Recently the design of the thermit rail weld for street railways and the equipment employed have been so perfected that it is possible to weld rails during the day on busy streets without interrupting traffic. Cars continue to operate over the track being welded throughout the entire process except for a short period during which the thermit reaction takes place and the weld is poured. Either inserts or undercutting may be employed in welding under traffic.

On Railroads

A comparatively recent development in thermit rail welding is in the railroad field where the tendency is toward greatly increased operating speeds and the rail joint problem has become acute both from the standpoint of safe operation and from that of maintenance expense. While more or less experimental in nature, a number of installations of continuous rails made up of quantities of standard rails thermit welded into long, jointless stretches are proving that the difficulties that were anticipated from expansion and contraction are by no means serious. In fact, with the type of track fastenings employed in the installation of these long rails, it is found that continuous rails, a mile and more in length, have little or no difference in movement at their ends between winter and summer than individual 39-ft. rails.

In addition to the above, thermit rail welding is employed by a number of railroads for welding short stretches of rail into continuous lengths through highway crossings, at station platforms, etc., where maintenance of mechanical rail joints would be difficult and might entail frequent opening of pavement.

Pressure Fusion Weld.—One type of thermit rail weld used in welding steam railroad rail is known as the *pressure fusion weld.* In this type of weld the bases and webs of the rail are fusion welded while the heads are welded by pressure alone and a full butt weld of the rail heads is assured.

In making the pressure butt weld, heating of the heads to welding temperature is brought about by means of the slag from the thermit reaction. The molds are so constructed that this slag completely surrounds the heads at the joint when the weld is poured. Pressure for butt welding is obtained by means of rail clamps which are drawn up to squeeze the rail heads together when they have been sufficiently softened by the heat of the slag.

Full Fusion Weld.—Another design of weld employed in welding of railroad rail is the so-called *full fusion* weld which is similar to the welds used in street railway work except that neither inserts nor undercutting are employed. Instead, a gap is left between the rail ends and thermit steel is poured into this gap to provide a fusion-weld of base, web and head.

In Coal Mines

In coal mines, where the majority of main haulage track is electrified, maintenance of rail joints and bonds is an important item. By substituting thermit welds for rail joints this maintenance expense is avoided and, at the same time, because of the improved electrical conductivity of the rails, power consumption is reduced appreciably.

Thermit welding of coal mine track is carried on in exactly the same way as in the standard method of welding street railway track.

Because of the generally restricted working space available and the lighter weight rails encountered, however, the equipment employed in mine work has been scaled down and preheaters, clamps, mold boxes and crucibles are all considerably smaller than those used in the open.

Special Work

An interesting and important additional application of thermit rail welding is the making of frogs, mates and crossings out of short lengths of rail welded together into desired designs. Even elaborate pieces are readily fabricated in this way, using the same equipment and methods that are employed in track welding.

Locomotive Repairs

Locomotive repairs made by the thermit process include repairs to broken frames, driving wheel spokes and the like.

This work differs little from general repair work except that in most cases the sections to be repaired are members of more or less complicated castings or forgings and in order to maintain proper alignment, careful attention must be paid to the control of expansion and contraction during welding.

Cast-Iron Repairs

The thermit process, while entirely suitable for the welding of cast iron, cannot be used on all work of this nature be-

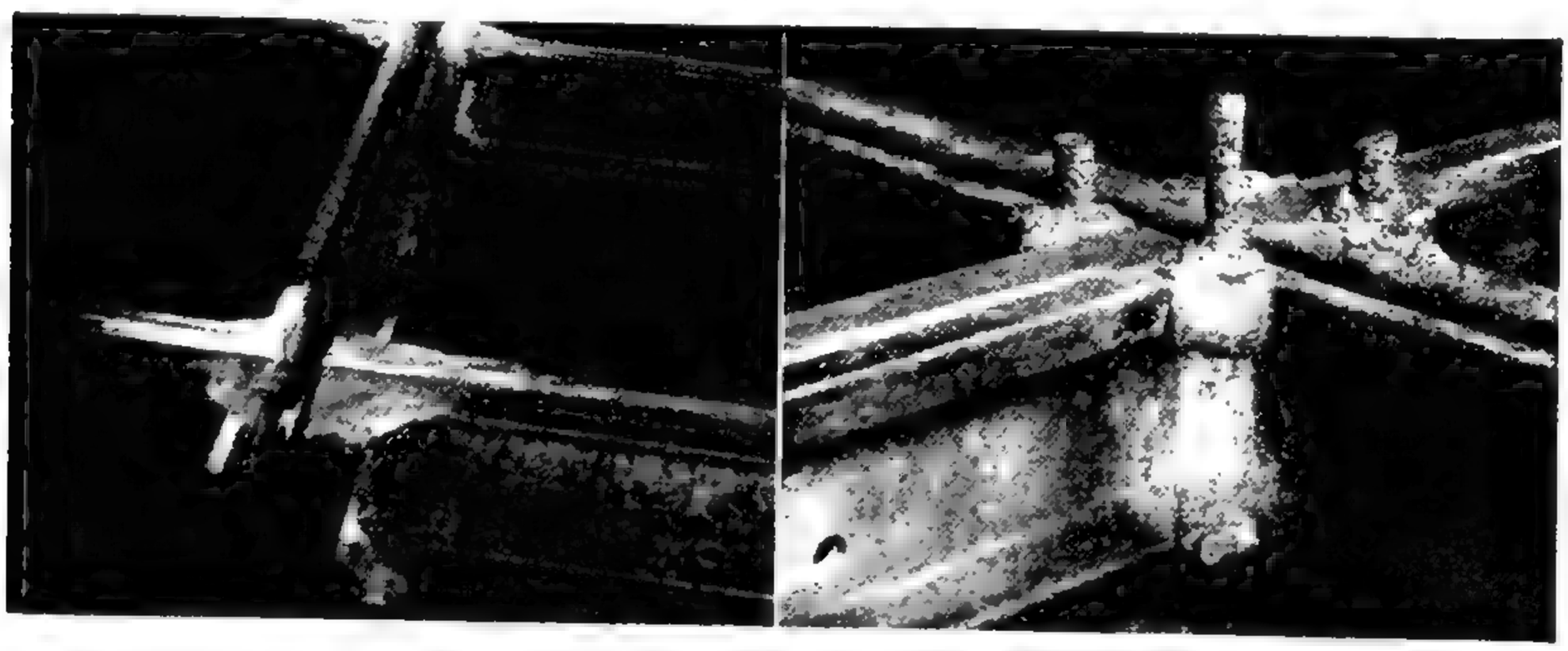

Fig. 11.—Completed 90 Deg. Frog and Method of Welding

Special work of this type is economical to fabricate and is amply rugged (Fig. 11). Compromise joints may also be made in this manner and have the advantage of being continuous pieces of rail varying in section rather than complicated and comparatively costly mechanical joints.

Where only an occasional piece of special work is to be fabricated, wax patterns are used rather than the permanent patterns used in track welding. Molds are rammed on the rail very much in the same way as in making a thermit repair to a shaft or machine frame. When a number of pieces are being made continually, however, the procedure is readily reduced almost to a manufacturing basis through the use of sets of permanent patterns designed to fit various rail sections and adjustable to different angles of intersection.

cause of the difficulty under certain conditions of allowing properly for the shrinkage of the weld metal when it cools. Contraction of thermit steel is approximately double that of cast iron so that, generally, if the length of the crack to be welded is more than eight times the thickness of the section, the difference in shrinkage along the line of fracture will result in small hairline cracks in the weld. These cracks, however, appear perpendicular to the line of the weld and are not always of great importance so far as strength is concerned.

Marine Work

New Construction

In addition to repair work, thermit welding is also used in the marine field for the fabrication of heavy parts. The stern frames of practically all of the

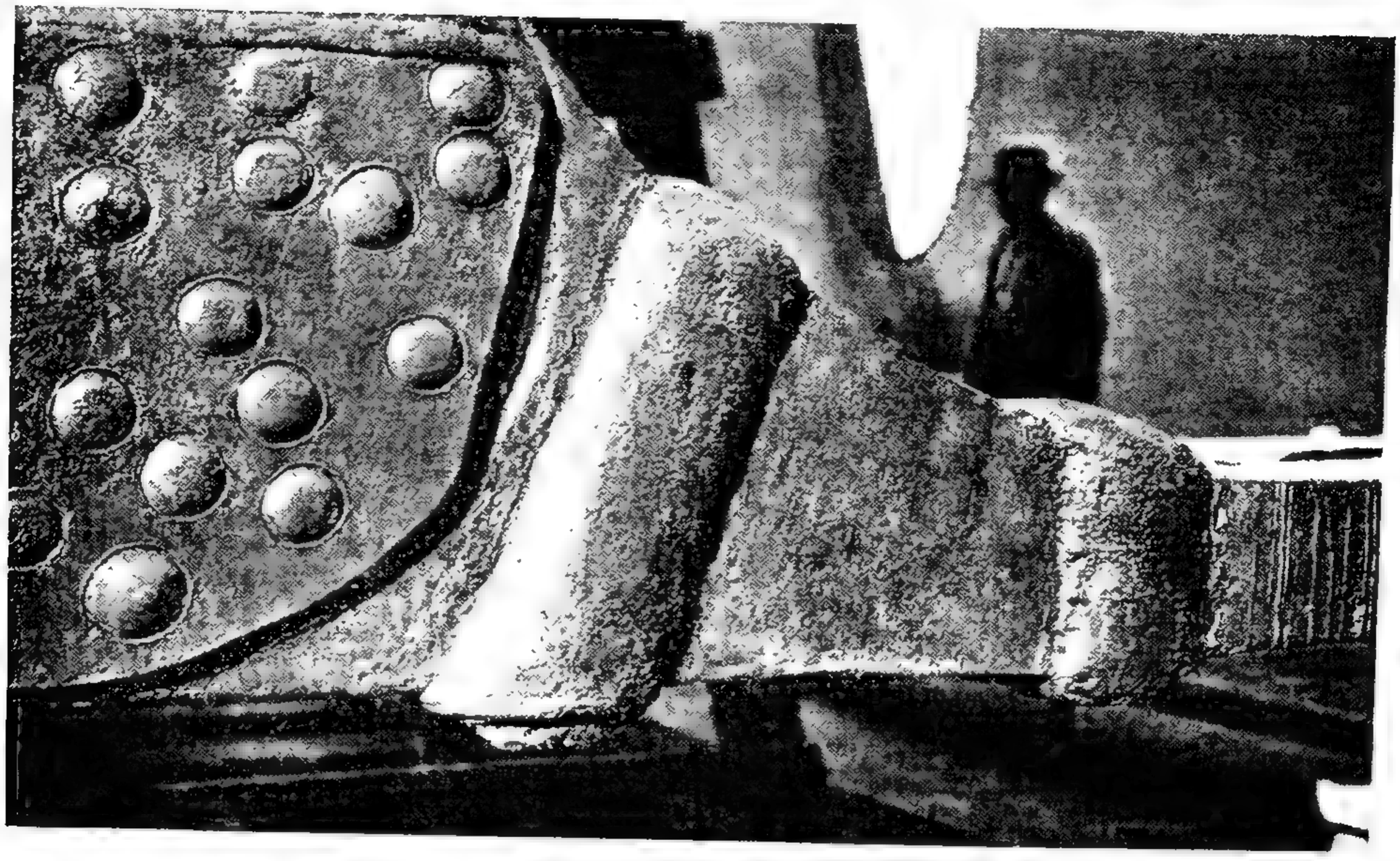

Fig. 12.—Typical Marine Repair

several hundred Liberty and Victory ships built for the U.S. Maritime Commission, for example, were fabricated in this manner. Ships classified as C-1, C-2 and C-3, which are to be equipped with contra-rudders for greater speed, have stern frames made in five sections, thermit welded to form the complete frames. The thermit welding of these frames as compared with a mechanized type of joint or with arc-welded construction resulted in the elimination of a considerable amount of machining and a corresponding saving in time and expense.

Repairs

The thermit process is used extensively in the marine field for welding broken stern posts, stern frames, rudder frames, rudder posts, shafts and propeller struts. It has been approved by all leading underwriters for this class of work.

The methods employed are similar in every respect to those used in general repair work and usually consist of welding at the point of fracture. In some cases, however, where there is more than one break or where considerable defective metal must be replaced, it is desirable to install a new billet or forging to replace the defective part. The new section is simply welded in place by means of two thermit welds. Figure 12 shows a typical marine repair.

BIBLIOGRAPHY

1. *Characteristics of Thermit Welds on Forgings*, J. H. Deppeler, Heat Treating and Forging, March 1940.
2. *Stern Frame Construction with Thermit Welding* M. L. Smith, Nautical Gazette, October 1942.
3. *Stern Frame Problems—Victory vs. Liberty Ships*, C. P. Hubert, The Logs, May 1944.
4. *Thermit Welding in Heavy Fabrication*, K. R. Rose, Metals and Alloys, December 1944.
5. *Modern Welding Practice in Ship Construction*, J. H. Deppeler, Nautical Gazette, March 1945.
6. *Welded Rail*, P. O. Ferriss, Railway Engineering and Maintenance, May 1946.
7. *Thermit Welding in Steel Plant Maintenance*, J. H. Deppeler, Iron and Steel Engineer, September 1946.

CHAPTER 20

INDUCTION WELDING*

INTRODUCTION

THE HEATING of metals can be achieved by two general methods: The metal can be heated by exposure to an external source, such as a flame, an oven, an arc; or it can be heated internally by passing an electric current through it. If the current is supplied by connecting the metal to a battery or generator, the method is known as resistance heating. If the current is produced, or induced within the metal itself, the process is called induction heating.

The existence of the induced current can be explained in the following manner. When a conductor is placed in a magnetic field that is changing with time, an electromotive force is generated within the conductor. If the ends of the conductor are joined so that a closed circuit is formed, a current will flow. The magnitude of the electromotive force, or voltage, is proportional to the rate of change of the magnetic field. If the rate of change, or frequency, of the field is rapid, large voltages can be generated. The presence of large potential differences in a closed circuit will cause correspondingly large currents to flow.

Frequencies above 300 cycles per second are used in the industrial field of electrical heating. Large sheets of steel are warmed to accelerate the drying of paint by exposing them to magnetic fields in the range of 360 to 960 cycles per second.

Frequencies of 3000 cycles are often used for the melting of small pots of metal. The metals are brought to a melting point in a very few minutes through the current induced by the windings of the inductor coil. The windings do not touch the metal, but merely surround it. The heating is caused by the high-frequency current no matter how the current is produced.

Still higher frequencies, up to about 200,000 cycles per second can be produced by spark-gap equipment. Above this range, the generators are limited to electronic oscillators. Figure 1 illustrates one of the major circuits in use. Section *R* represents schematically the mercury-tube rectifier used to convert the 60-cycle output of the high-voltage transformer to the direct current utilized by the oscillator circuit *S*.

Section *T* is a portion of the circuit consisting of the inductor coil surrounding the *work* or metal to be heated. Equipment of this type is widely used by industry for heat treating, hardening, and soldering or brazing.

The induced high-frequency currents commonly employed in heating metal parts to soldering or brazing temperatures may also be used to weld metals. The fundamental principle is very simple. A high-frequency induced current is made to flow through the edges of the parts to be joined; these edges suddenly melt, and form narrow strips of liquid metal. Because of their cohesive properties, these strips of molten metal flow together and form a bead that bridges the joint. The entire operation is carried out in a few hundredths of a second.

The reduction of this simple principle to a practical welding installation may require considerable equipment and experience. As in most forms of resistance welding, the magnitude of the current and the time interval must be accurately controlled.

The heating of the metal is caused by the I^2R loss, I being the induced high-frequency current. The first fundamental requirement of induction welding is that the parts to be joined must constitute a closed path or short-circuited turn. This fact excludes seam welding and, in general, indicates that the entire area being

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* Prepared by R. J. Bondley, General Electric Co.

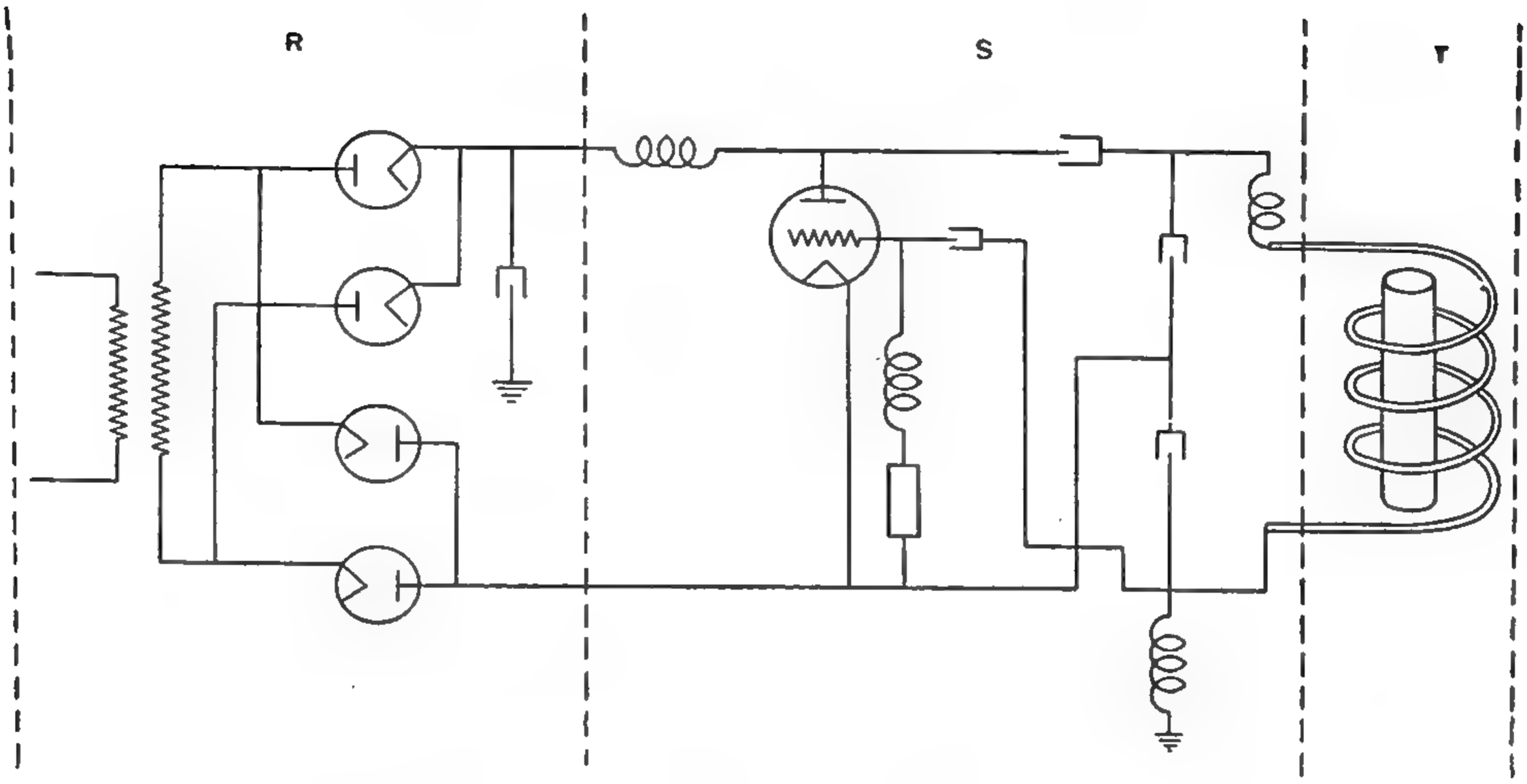

Fig. 1.—Electrical Circuit for Induction Welding

joined must be melted with a single application of power. Thin-walled cylinders or discs of the type illustrated in Fig. 2 are the most ideal shapes for welding.

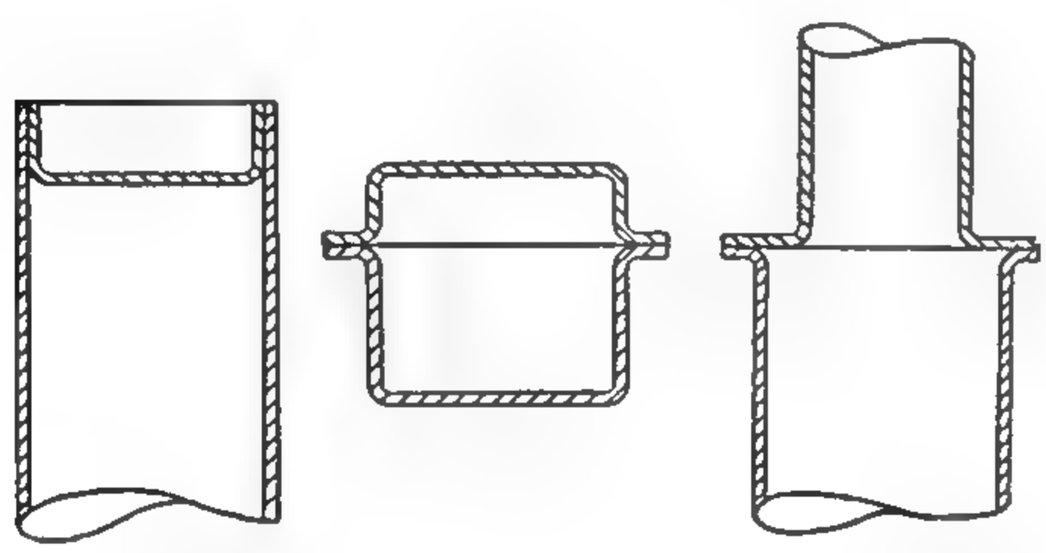

Fig. 2.—Ideal Shapes for Induction Welding

Here the areas being heated are determined by the geometry of the parts as well as by the shape and proximity of the inductor coil.

EQUIPMENT USED

Since high-frequency currents flow mainly on or near the surface of metals and since only the part of the metal that carries the current is heated, the weld is limited to shallow areas. In fact, the depth of penetration of the current is proportional to $\sqrt{1/f}$, f being the frequency of the induced current. Thus, the higher the frequency, the more pronounced is the skin effect. If the frequency is lowered, the current penetrates deeper and a larger volume of metal is heated. More power is needed to bring this increased volume of metal to welding temperatures. It is evident that a compromise frequency is necessary to balance the required power against the depth of penetration of the weld. It has been found that an oscillator having a frequency of about 500 kilocycles per sec. is a satisfactory power generator for welding ferrous alloys.

Attempts to weld copper by this process have not been successful. Because of the high thermal and electrical conductivity of copper, very strong currents are required to bring localized areas to the melting point. These induced currents are accompanied by strong magnetic forces. As fast as the copper is melted, the magnetic forces eject the melt from beneath the coil in a shower of droplets. The effect is as though a high-pressure air jet was turned on the melted copper. As a result there is little or no molten metal to bridge the gap when the current is turned off.

Power generators for this frequency are limited to vacuum tube oscillators. Such devices have inherently high output impedances. On the other hand, the heating coil must be closely coupled to the work and must be limited to a single turn in order to concentrate the current. It is, therefore, a low impedance load. To transfer a maximum amount of energy from the generator to the load, some impedance-matching device is necessary.

An air-core transformer is commonly employed to couple the work coil to the oscillator.

In its simplest form, the transformer consists of a helix of copper tubing used as a primary, and a sheet of copper enclosing this helix and forming a single-turn secondary. It has been found by experience that the actual design of this transformer is not excessively critical, and that its appearance and construction may vary widely. Since the whole system is closely coupled, the characteristics of the load are reflected back to the generator. The turn ratio is of some importance but not critical, and usually varies from 30 to 1, to 8 to 1. Small diameters of the parts being welded require a large number of primary turns.

Generally the transformers are of the type illustrated in Fig. 3 varying from 4 to 6 in. in diameter, and from about 6 to 20 in. in length, the length, of course, being set by the number of turns of the primary.

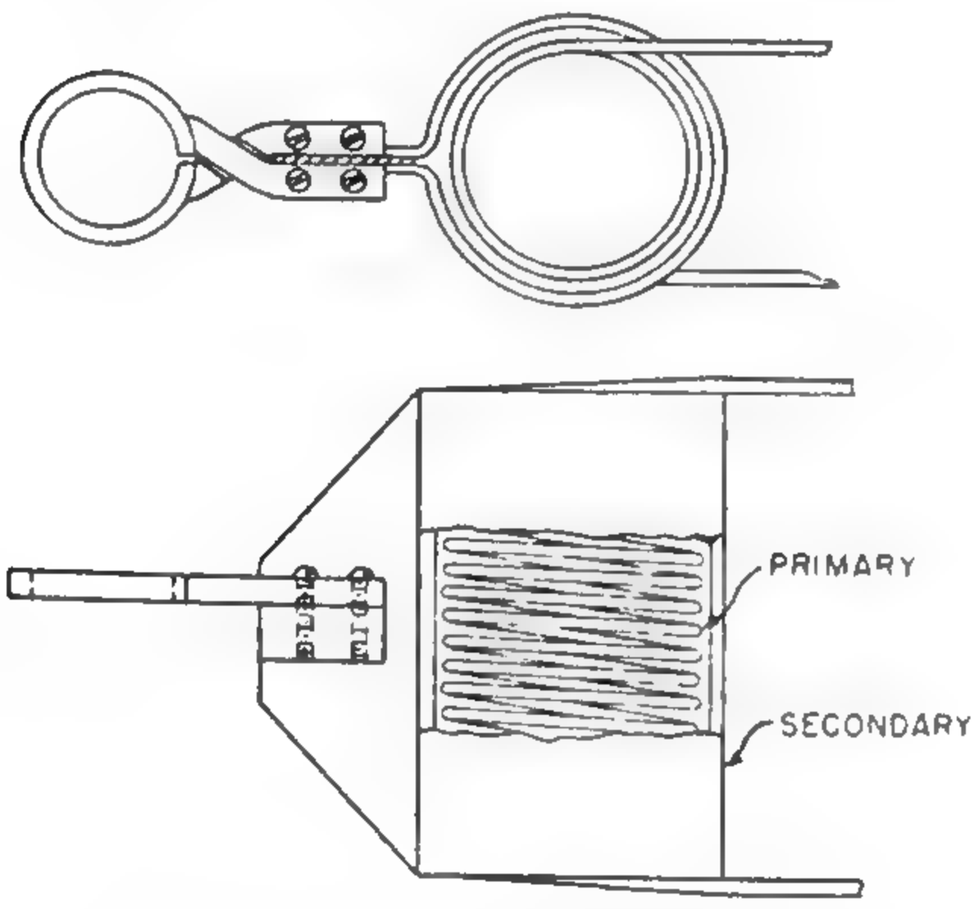

Fig. 3—Induction Weld Transformer

In low-power installations an air space of one-quarter inch or greater may be used. In the higher-power generators, i.e., 50 kw. or more, it may be necessary to fill the space with insulation. The spacing between the helix and the single-turn secondary is made as close as practical to keep the coupling tight. A cylinder formed from sheets of mica is very effective.

The secondary of the transformer together with the work coil forms a low-voltage, high-current circuit. The type and length of the conductors leading from the single turn secondary to the work coil are of great importance. The necessity of keeping the impedance of these leads as low as possible cannot be stressed too highly. The preferred design consists of fastening the work coil directly to the transformer, eliminating leads entirely. In cases where this cannot be done, the only alternative is to keep the leakage flux in the leads low by making the impedance low. This can be done by using flat plates spaced very close together for the leads, or by using a coaxial conductor of fairly large diameter, and with smallest possible clearance consistent with voltage requirements between the inner and outer leads.

It has been stated that the work coil is a single turn of copper. To assure very local heating, the coil is spaced about $^1/_{16}$ in. from the work. Coils of the type illustrated in Fig. 4*A* often leave an unwelded spot on the work because of the gap formed where the leads are attached. By crossing the leads, as illustrated in Fig. 4*B*, the cold spot is eliminated, and uniform heating around the periphery is obtained. When the duty cycle is high, it is necessary to water cool both the transformer (primary and secondary) and the work coil in order to dissipate the heat generated by the transformer losses.

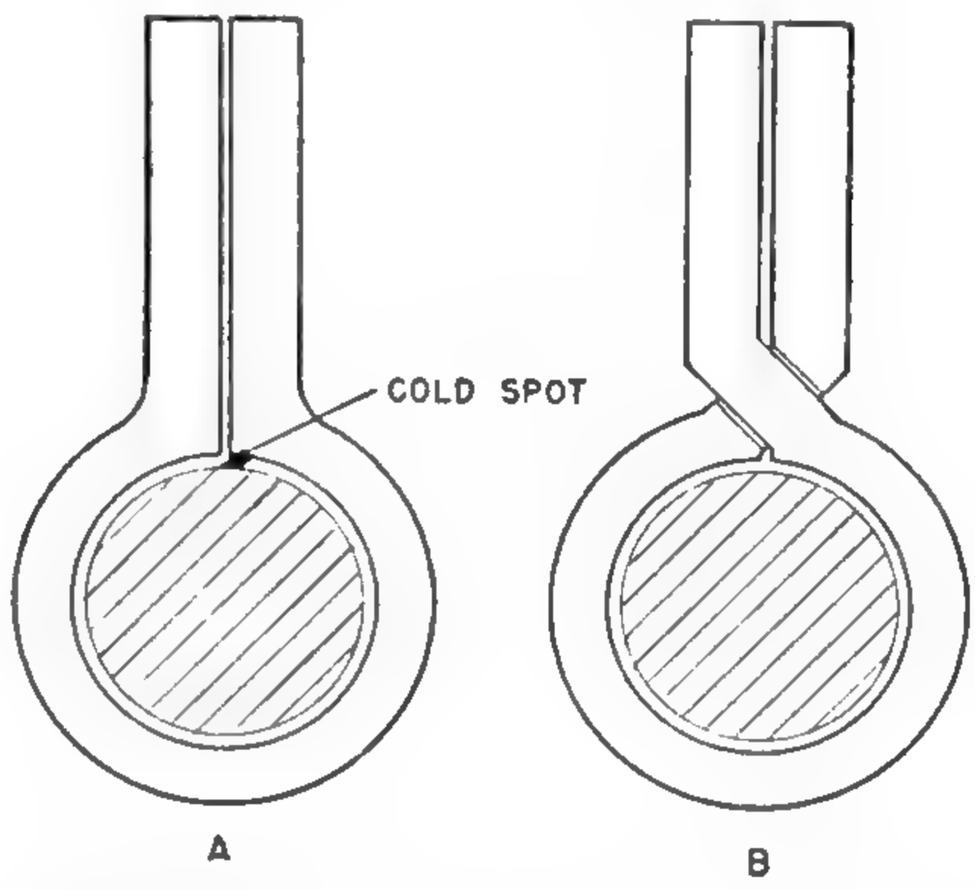

Fig. 4.—Work Coils—Improper and Proper

TIMING DEVICES

There are several means by which accurate timing can be obtained. The conversion of 60-cycle power into heat energy within the work is carried out in

several steps. The first is in the rectifier unit, which converts the 60-cycle power to high-voltage direct current. The second is in the oscillator unit which in turn generates high-frequency power from the direct current. The third step is in the coupling of the high-frequency power to the work itself. The power can be controlled at various points along the system, usually depending upon the particular installation or the economics of the case.

The 60-cycle power itself may be controlled. If the installation is single phase 60 cycles, a synchronous timer of the type used for spot welding will give exact applications of power. In 3-phase systems, synchronous timers become rather complicated and other means of applying the power pulse may be more expedient. Whenever the power is controlled from the 60-cycle source, it can only be varied in time by definite steps, each step being one cycle or $^1/_{60}$ of a second.

The rectifier itself can be used to turn the power pulse on or off, provided the rectifier tubes are grid controlled. The grids in this case are biased so that the rectifier is inoperative during the stand-by period. For welding, the grids are pulsed positive by some timing device. Here, again, the time is some fraction of 60 cycles.

Perhaps the most practical timing system, as judged from the equipment required, can be secured by controlling the oscillator tube itself. The grid of the power tube is biased negative and beyond cutoff so that the circuit is non-oscillating even with anode voltage connected. Removal of the bias will allow the circuit to oscillate for the length of time the bias is off. Here the timer is controlling a direct current and infinite variations or adjustments of the pulse length are possible. The power requirements of the oscillator grid are low so that the timer itself can be of low capacity as compared to the total power of the generator itself. There are numerous schemes for timing this pulse electronically, the method used depending upon the peculiar requirements of the installation.

COMMON APPLICATIONS

When one considers the rather large investment in equipment and the limited scope of induction welding, the question naturally arises as to when its use can be justified. There are several conditions where induction welding is particularly valuable.

First, the process is inherently one of high efficiency. In a well-designed installation as much as 50% of the energy drawn from the line appears in the form of heat in the work.

Circulating, or wattless kva, is confined to the oscillator circuit and does not appear in the 60-cycle feeder lines. This is in sharp contrast to the typical low-power-factor, spot-welder load.

In making annular welds, an induction welding installation drawing a maximum of 100 kw. will weld parts that would require as much as 1000 kva, if done on a projection welding machine. The induction welding equipment can operate from a balanced 3-phase power system, whereas the projection welding machine is usually operated on single-phase.

Since a projection welding machine is essentially single-phase many power companies object to system disturbances set up by these machines. Often, too, the total generated kva. is not large enough to supply the peak demand. This is particularly true in small communities.

Induction welding is by nature a mass-production system. Only a few hundredths of a second are required to complete a weld, and since it is not necessary to make electrical connections to the parts to be welded, the output of the system depends largely on how fast the parts can be placed in welding position.

Maintenance is low because electrodes do not touch the parts, and hence do not have to be refaced as in the annular projection weld.

Then too, as the time of welding is short and the heating is very local, there is a minimum amount of oxidation and discoloration of the parts. Small vessels containing materials that would be damaged by an arc or a flame can be safely welded by induction welding.

It is practical to make the welds in almost any atmosphere by the simple expedient of enclosing the parts and the heating coil in a bell jar containing the desired gas. Satisfactory welds have even been made in a high vacuum by connecting the bell jar to a vacuum pump. For example, a cover can be welded on a small container in a vacuum, and the finished part will have complete freedom from exhaust tubings or other protruding

tips necessary for evacuation by other methods.

Induction welding has been most successfully employed in joining steels ranging in thickness from 0.010 in. to about 1/8 in. and in diameters up to about 3 inches. Shapes other than round or oval can be welded by modifying the spacing between the coil and the work to give an even distribution of heat. Typical applications are shown in Fig. 5.

Copper, aluminum and other high-conductivity metals are not well adapted to induction welding methods, although there may be exceptions to this statement for particular cases.

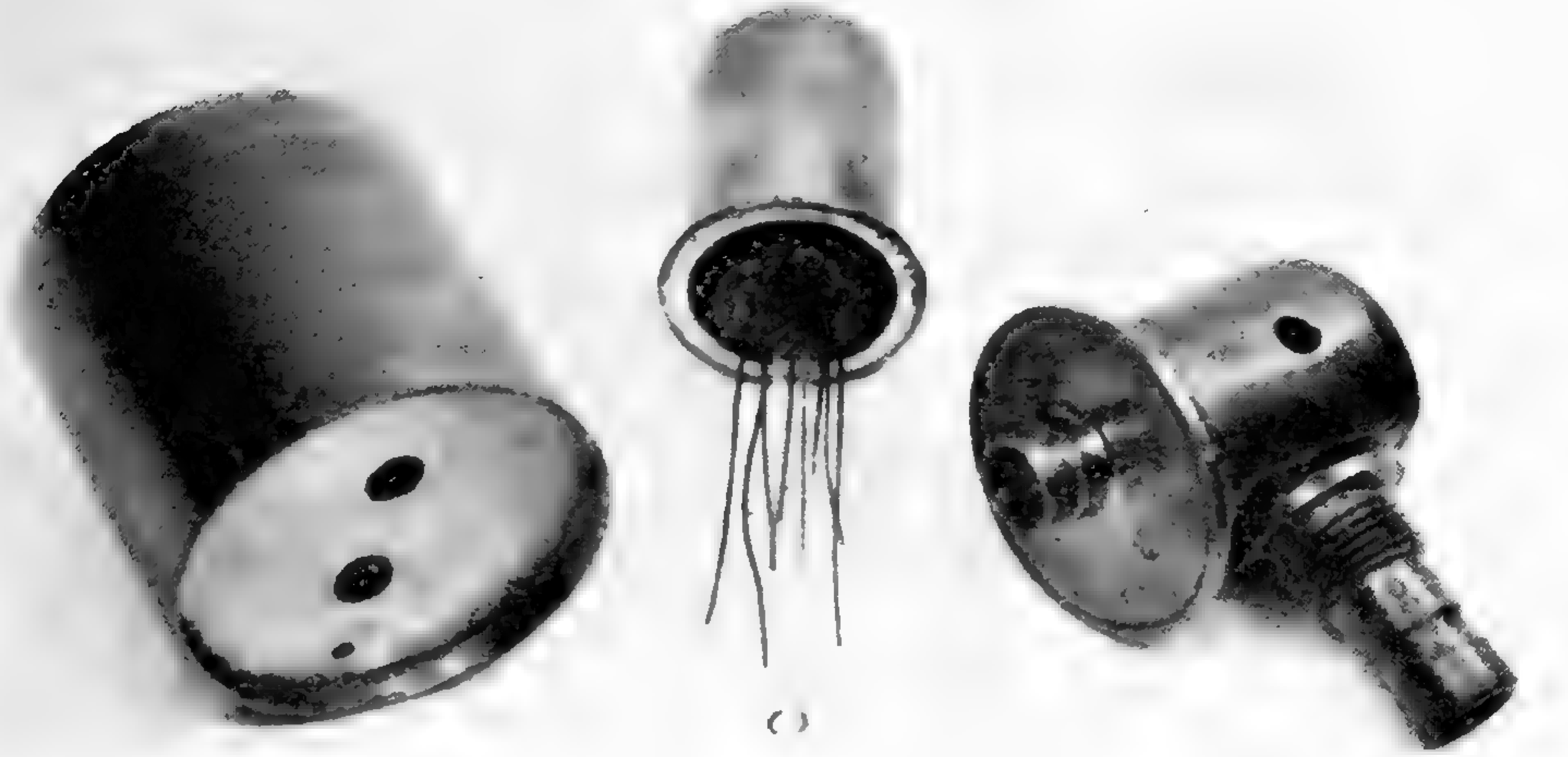

Fig. 5.—Typical Metal Parts Assembled by Induction Welding Methods

BIBLIOGRAPHY

1. *Electric Heating by the Proximity Effect*, E. Bennett, Welding Journal Res. Suppl., October 1936.
2. *The Theory and Practice of Industrial Electronic Heating*, J. P. Jordan, General Electric Review, December 1943.
3. *High-Frequency Induction Heating*, Frank W. Curtis, McGraw-Hill Book Co., Inc., 1944.
4. *High-Frequency Induction Heating*, Wesley M. Roberts, Mechanical Engineering, July 1945.
5. *Problems in the Design of High Frequency Heating Equipment*, Wesley M. Roberts, Proceedings of Institute of Radio Engineers, July 1946.
6. *Induction Heating*, American Society for Metals, 1946.
7. *Electronics for Industry*, W. I. Bendz, John Wiley & Sons, Inc., 1947.

CHAPTER 21

SURFACING AND METALLIZING*

A. SURFACING

FUNDAMENTALS OF PROCESS

Definition and General Description

SURFACING† IS THE process of applying by arc or gas welding, an integral layer of metal of one composition onto a surface, edge or point of a base metal of another composition. A wide variety of characteristics can be secured by proper choice of surfacing metals, and the applied layer may be as thin as $^1/_{32}$ in. or as thick as necessary. If the surface metal is intended to resist hard or abrasive wear, steel base or especially hard, surfacing alloys may be used. If the surfacing is intended to resist corrosion or friction-type wear, bronze or other suitable corrosion-resisting alloys may be employed.

Classification and Properties of Surfacing Materials

A multitude of alloys and metals are suitable for surfacing operations, and most of them can be deposited by any of the conventional manual or automatic welding processes. By proper choice of these alloys and of conditions of deposition and heat treatment, surfacing deposits can be made to withstand a wide range of services. Although cursory examination would indicate that the choice of the best alloys for any particular use would be difficult, it has been found entirely feasible to classify all the alloys in an orderly fashion and to relate their general use to this classification. The basic classification is outlined completely in Chapter 38.

Selection of Materials

In order to select intelligently the correct surfacing material for any particular application, the user should first determine or be aware of those factors which cause the deterioration of the part.

In general, the attack on the part will involve one or more of the following: sliding metal-to-metal contact, either with or without lubrication; rolling contact, either in a nonmetallic bed or against a metallic surface; heavy shock or impact loading which must be resisted without deformation or serious cracking; varying earth abrasion or other types of wear that may cause metal loss; corrosion, either from atmospheric attack or other corrosive media; and resistance to deformation when hot. Other less well-defined factors, such as machinability, freedom from porosity and ease of application have a distinct bearing on the alloy to be used. Seldom does any one of these factors dominate, but each must be separately recognized in an analysis of surfacing requirements.

It is difficult to do more than generalize on the steps to follow in choosing a suitable material for a specific service. A great many decisions of this nature are based on experience with the particular type of service and except where a relationship has been developed between the microstructure or other characteristics of metals and the type of service to which they are most suitable, the choice will be dictated mostly by experience either of the user or of the supplier of the materials.

There are a few wear tests that have been validated against wear under field conditions and that have provided reproducible results. They are subject to the same limitations mentioned above, that one

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* Prepared by a committee consisting of A. R. Lytle, Union Carbide & Carbon Res Lab., *Chairman;* H. S. Avery, American Brake Shoe Co.; F. C. Kroft, Haynes Stellite Co.; H. W. Sharp, Stoody Co.; A. P. Shepard, Metallizing Engrg. Co.; Stephen Smith, National Forge and Ordnance Co

† The term surfacing has been adopted to embrace all coating operations referred to previously as hard surfacing, bronze surfacing, padding or facing.

type of wear may have no dependable relationship to another type. As a further caution, it is important that wear test results be questioned unless the test method and apparatus have proved reliable and valid. This means that the test data should be satisfactorily reproducible and should provide an acceptable correlation with properly controlled field tests. Correlation with field results gives an assurance that essential wear factors have been properly included in the test. It should be noted that hardness testing, while it is customarily used as a substitute for wear tests, provides no assurance of field performance in an unvalidated situation.

There are, however, a few generalizations that may be employed in guiding a first choice. Hardness is usually directly related to resistance to abrasion, shock or impact wear and, for maximum resistance to these types of wear, the harder alloys are to be preferred. Together with the hardness gradation, comparison can be made of the relative toughness of the deposits. This factor is of great importance where the structural strength of the deposit is depended upon, or where impact loading occurs, but in other cases this factor may be unimportant. Again, judgment and experience will serve as guides.

Table 1 has been prepared to provide a first approximation to the choice of surfacing metal for a given generalized type of service. The ratings have been assigned on the arbitrary scale of 10 to 100, 100 implying the best obtainable and 10 rather poor for that usage. Clearly, all the manifold instances of wear are not specifically listed but it is believed that the items under which the alloys are classified represent the more or less elementary types of service which cause deterioration of the part. Most severe services embrace combinations of several conditions and the choice of alloy may be influenced by its overall or combined utility rather than by its special value for one condition. In some applications the recommendations indicated by this table may not provide the most satisfactory service but, in such cases, other factors which are usually of small importance may have had a strong influence. For instance, the influence of chemical corrosion has not been introduced in this table and in some uses this factor may be dominant. Aside from such unpredicted conditions, the table offers a ready means of choosing an alloy or group of alloys which would most probably give the best performance under given service conditions.

Some services require high hardness with freedom from porosity and the ability to attain a high polish. For such services, it is not always possible to use the most wear-resistant alloys, namely, the tungsten carbides, because deposits with these metals are heterogeneous and wear to a rough surface.

It is frequently difficult to produce a perfectly machined or ground surface on carbide deposits due to the presence of the very hard particles.

Where corrosion resistance or maintenance of appearance under atmospheric conditions is a factor, a rust-resisting or even corrosion-resisting alloy is used. Frequently, corrosion resistance is the dominant factor or it may be combined with other factors such as wiredrawing or sliding metal-to-metal contact. Several alloys are indicated for this type of surfacing and consideration should be given here to alloys of Type *II* of Table 1, or to the several grades of brass, bronze or nickel alloys.

Resistance to hot-deformation is another requirement, and, for this, alloys are needed that have high hot-hardness. Several types of alloys, such as Types *I-C* and *II*, are suitable for this service. Additionally, some services require a high degree of toughness which must be preserved at high temperatures. Some alloys in the high-nickel group, Types *V-B* and *V-C*, have been especially successful for this type of application.

Metal-to-metal sliding and seating wear is different from the soil-to-metal kind of wear encountered in earth-handling equipment. Although hardness is important in preventing galling and deformation, the best resistance to such service is usually provided by a combination of dissimilar metals. For that reason, the bronzes have a very wide field of application, such as for sliding surfaces and on seats for valves. These alloys are available in various degrees of hardness as, for some services, hardness is a parallel requirement. Corrosion may also be a factor, as in corrosive liquids or even for water service, but this can be provided for by a proper choice of alloy. Some of the high-copper or nickel alloys and the

cobalt-base, nonferrous alloys have excellent corrosion resistance coupled with good resistance to sliding wear.

Cost is frequently an important factor in the choice of alloy. For many applications, the ideal alloy would likewise be the highest priced, so a balance must be made between the benefits gained by the use of this alloy, the total cost of the item, the comparative service given by the use of slightly inferior alloys and the cost of replacement of the worn part. Frequently it is found that the higher priced alloy is well justified by its service performance. For many applications, rust resistance would be desired for the sake of appearance, but the cost of non-rusting metals might be too high, especially when the same service could be produced with materials that rusted slightly. This factor of cost cannot, however, be evaluated on the same basis as hardness for instance, so no mention of it is included in Table 1.

WELDING PROCESSES

Gas Welding

An important advantage of surfacing

Table 1—Comparative Ratings of Surfacing Alloys

	Hardness	General Atmospheric Corrosion Resistance	Resistance to Earth Abrasion	Resistance to Hot Deformation	Service Under Heavy Abrasion	Service in Sliding and Rolling Wear[a]
I. Ferrous						
A. Hardenable Alloys						
1. Carbon Steels						
a. Low	10	10	10	10	10	20
b. Medium	10–40	10	10	10	10	50
c. High	20–60	10	20	10	10	50
2. Low-Alloy Steels						
a. Low carbon	10	10	10	10	10	30
b Medium carbon	20–40	10	10	10	20	50
c High carbon	20–60	10	20	20	20	50
d. Cast-iron types	20–60	10	40	20	20	40
3. Medium-Alloy Steels						
a. Medium carbon	20–40	20	20	30	50	60
b. High carbon	30–50	20	40	50	80	60
c. Cast-iron types	30–70	20	50	60	50	40
4. Medium-High Alloy						
a. Low carbon	20–40	20–50	20	40	30	40
b. Medium carbon	30–60	20–30	40	50	70	60
c. High carbon	40–80	20–30	60	50	80	40
d. Cast-iron types	40–80	20–30	70	50	50	40
5. High-Speed Steel	80	20	40	70	40	40
B. Austenitic Steels						
1. Chromium and Cr-Ni						
a. Low carbon	30	90–100	20	20	30	30
b. High carbon, low nickel	40	90–100	20	40	50	30
c. High carbon, high nickel	40	90–100	30	40	50	30
2. High manganese	40	50	20	20	80	50
C. Austenitic—not usually heat treated						
1. High-chromium Iron	60	60–80	70	80	80	80
2. High-Alloy Iron						
a. 1.7% carbon	70	60–80	60	60	70	70
b. 2.5% carbon	70	60–80	70	60	60	80–90
c. Very high alloy	80	60–80	80	60	50	90–100
II. Cobalt Base Alloys						
A. Low Alloy	40	90–100	50	100	80	90–100
B. High Alloy	70	90–100	70	100	60	100
III. Carbides						
A. Inserts	100	60–80	100	100	50	100
B. Composite	75–100	30–60	100	...	70	...
C. Powder	.....	.....	100	...	70	...
IV. Copper Base						
A. Copper-Zinc	20	60–80	20	10	10	80–100
B. Copper-Silicon	25	60–80	20	10	10	50–70
C. Copper-Aluminum	25–40	60–80	30	10	10	70–90
V. Nickel Base						
A. Nickel-Copper (Monel)	20	80–100	20	10	20	20
B. Nickel-Chromium (Nichrome)	30	80–100	40	70	40	60
C. Nickel-Chromium-Tungsten-Molybdenum (Hastelloy)	50	90–100	50	90	60	80

a In combination with suitable companion alloy.

by gas welding is that the surfacing layer is applied by flowing the metal onto the underlying surface through the medium of *sweating* or *tinning*. These terms are used to describe the formation of an apparently lower-melting-point constituent which enables the metal being applied to flow onto the base metal without appreciable melting of the base metal. The term sweating refers to the action that takes place in the application of high-melting-point ferrous, nickel and cobalt-base alloys due to the use of an excess-acetylene flame. This flame carburizes the extreme surface of the base metal, thereby lowering the melting point of the film and providing a liquid medium on which the surfacing metal is immediately flowed. The layer of carburized metal is on the order of 0.001-in. thick and is absorbed by alloying with the molten surfacing layer. Gas-welded deposits can be made under these conditions, with penetration of less than 0.01 in. into the base metal. The term tinning is the corresponding term that describes the action that occurs in surfacing with bronze or copper alloys. In this case, it is more nearly a cleaning action due to the action of the flux or flame that prepares the base metal just ahead of the welding action, and which thereby permits capillary flow of the low-melting-point alloys onto the higher-melting-point base metal.

The size of the welding flame can be specified only in general terms, as it depends more upon secondary factors such as extent of the deposit, time limitation for the unit job, degree of preheat and type of metal being deposited, than upon the thickness of base metal. As a general guide, however, the torch should be one size larger than that recommended for welding base metal of that particular thickness. In any case a soft, quiet flame should be used to prevent laps, blowholes and poor adhesion of the deposit.

Application of Iron-, Nickel- and Cobalt-Base Alloys.—The character of the welding flame is very important for successful surfacing. For application of iron-, nickel- and cobalt-base alloys, an excess–acetylene flame is used. The best flame setting is that in which the feather, characteristic of excess acetylene in the flame, is three times the length of the inner cone (Fig. 1). This flame setting, when used by an experienced operator, produces the proper degree of sweating. Its use prevents a loss of carbon from the welding rod and in some cases causes an increase in the carbon content of the weld deposit by varying amounts ranging from 0.20 to 0.40% depending upon the alloy used. Flames with longer feathers of excess acetylene usually are not recommended as they are definitely of lower temperature, introduce too much carbon into the deposit, and produce poor-appearing welds, whereas flames with less excess acetylene do not provide the necessary carburizing conditions.

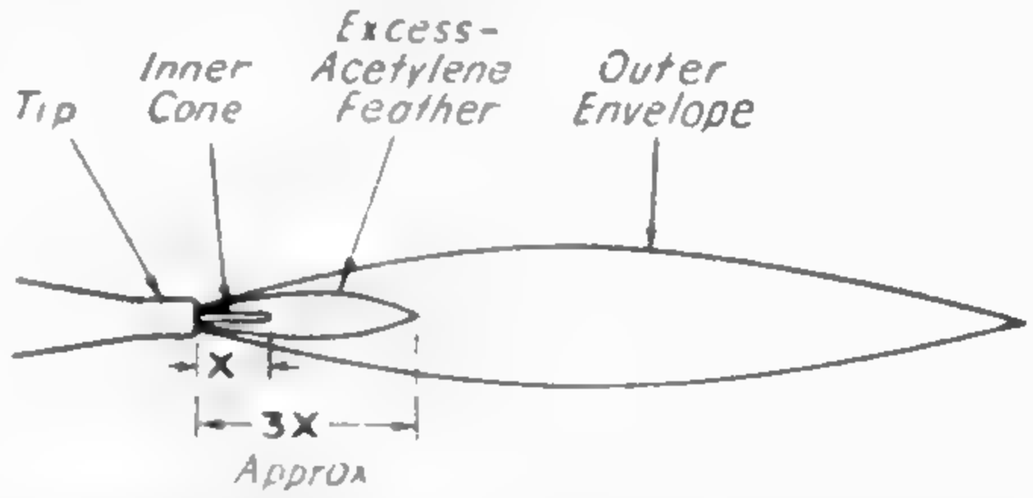

Fig. 1.—Approximate Dimensions of Excess-Acetylene Flame for Surfacing by Gas Welding

Base Metal Preparation.—All loose scale, dirt, rust or other foreign substances should be removed from areas to be surfaced, preferably by grinding or machining. Cleaning with a file, wire brush or sand blasting often leaves scale or other foreign material which must later be floated out during the surfacing operation. The use of flux has often been found desirable to maintain the clean condition of the surface and overcome oxidation that may develop during surfacing.

Although many surfacing operations are done on flat or extended plane surfaces, in some applications a highly localized deposit is desired. The best method of accomplishing this is to machine or grind grooves of the desired contour and depth. Suggested types of grooves for this purpose are shown in Fig. 2. It is important, in any such groove, that the corners and edges be well rounded to prevent overheating and alloying with the weld deposit.

Application of Bronze and Copper Alloys.—The application of the common brasses or bronzes to any of the compatible base metals follows the same principles outlined above for the steel in respect to cleanliness and the desirability of a groove for placement of a local deposit. However, a neutral or slightly oxidizing flame is recommended. An

excess-acetylene flame causes porosity, excessive fuming and poor adhesion without any compensating benefits. Also, a flux is necessary for practically all bronze alloys as there is no other provision for cleaning the base metal to permit the capillary flow of the bronze. The conventional fluxes recommended for the several rods are best, but in some cases the rods are already coated with flux.

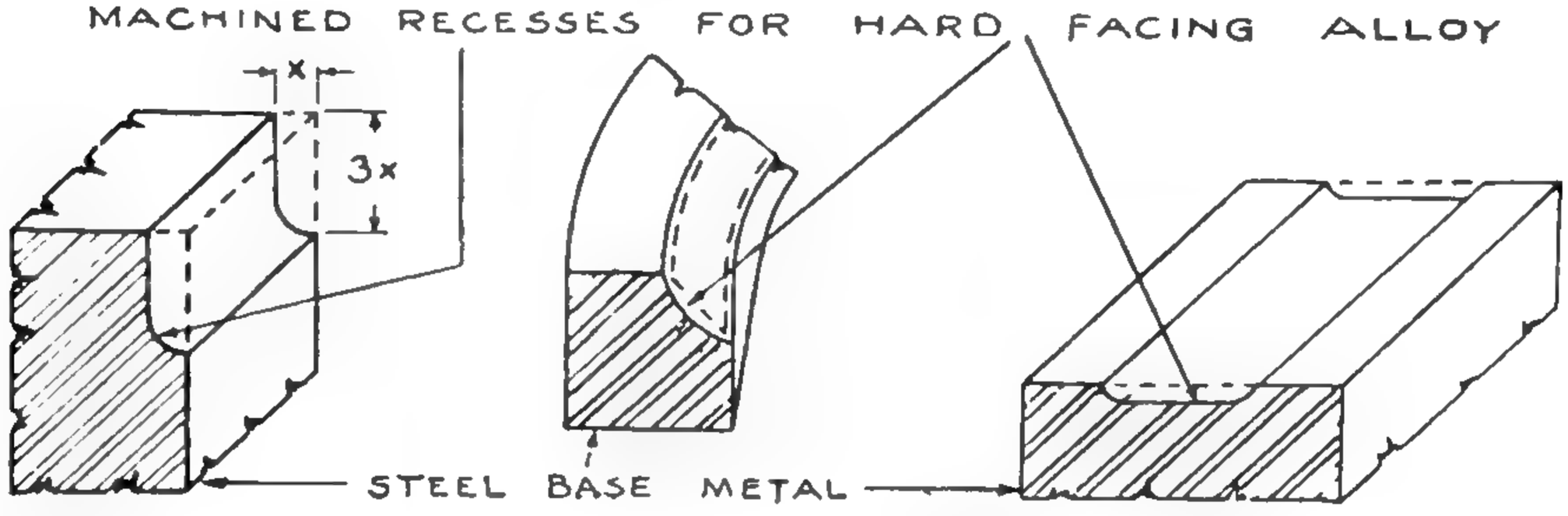

Fig. 2.—Suggested Types of Recess for Localizing Surfacing Deposits

Machine Gas Welding.— Many parts are surfaced on a production basis by mechanical methods. The possibility of mechanization depends upon the number of the parts, location of the surfaced area and type of surfacing metal. Two basic commercial methods are used for mechanized surfacing. These are called the cylindrical and straight-line methods. The cylindrical method, as the name implies, is for surfacing cylindrical objects, such as pump sleeves, collars, expeller screw bodies, and rolls. With this method, a number of rods are used so as to cover a wide area and to complete the application in one pass. The straight-line method is for surfacing a relatively narrow area, whether it be linear or annular. It is seldom that more than two welding rods are used. Parts which can be surfaced by this method are gate-valve seat rings and discs, ensilage knives, shear bars, circular slitter knives, gage strips and many other items of like nature.

With both of the above methods, multiflame welding heads are generally used to gain closer control over the deposit. The welding rod (or rods) can be fed under the flames either by gravity or by some mechanical device, depending on the nature of the job. Sometimes it is advantageous to employ an oscillating motion to aid in distributing the molten puddle. A photograph of a typical machine is shown in Fig. 3.

Many users of surfacing build their own machines for partial or complete mechanization. Suitable machines can be readily constructed with either a lathe, planer or welding positioner for a base and using combinations of standard, water-cooled, single or multiple-flame heads together with gravity-fed welding rods.

Special Merits of Gas Welding.— The use of gas welding for surfacing has definite characteristics which indicate its preference in a large number of applications. The prime merit is the lack of dilution with the base metal, hence the maintenance of characteristics of the deposited metal. This is especially important when the compositions of the base metal and surfacing metal differ considerably as in cases where high-chromium, high-cobalt or high-nickel alloys are used and where the bronzes and brasses are applied. In either manual or mechanical welding, dilution of the weld metal with the base metal can be maintained below 15% for the high-melting-point alloys. For the lower-melting-point brasses, the amount of dilution of the base metal is insignificant. In etched sections of surfaced parts, the contour of the deposited metal should conform very closely to the contour of the original grooves or surface. Any recession of the interface by more than 0.01 in. would

indicate excessive melting of the base metal.

The ease with which very thin layers of surfacing metal may be applied and the ease of running the surfacing metal out to corners and edges without overheating or building up thick deposits are also important. These characteristics are especially valuable in such operations as building up rail ends, where more than a $^1/_{16}$-in. thick deposit seldom is required, and more often the weld deposit is closer to $^1/_{32}$-in. thick. Other instances are the surfacing of edged tools, drill bits, etc.

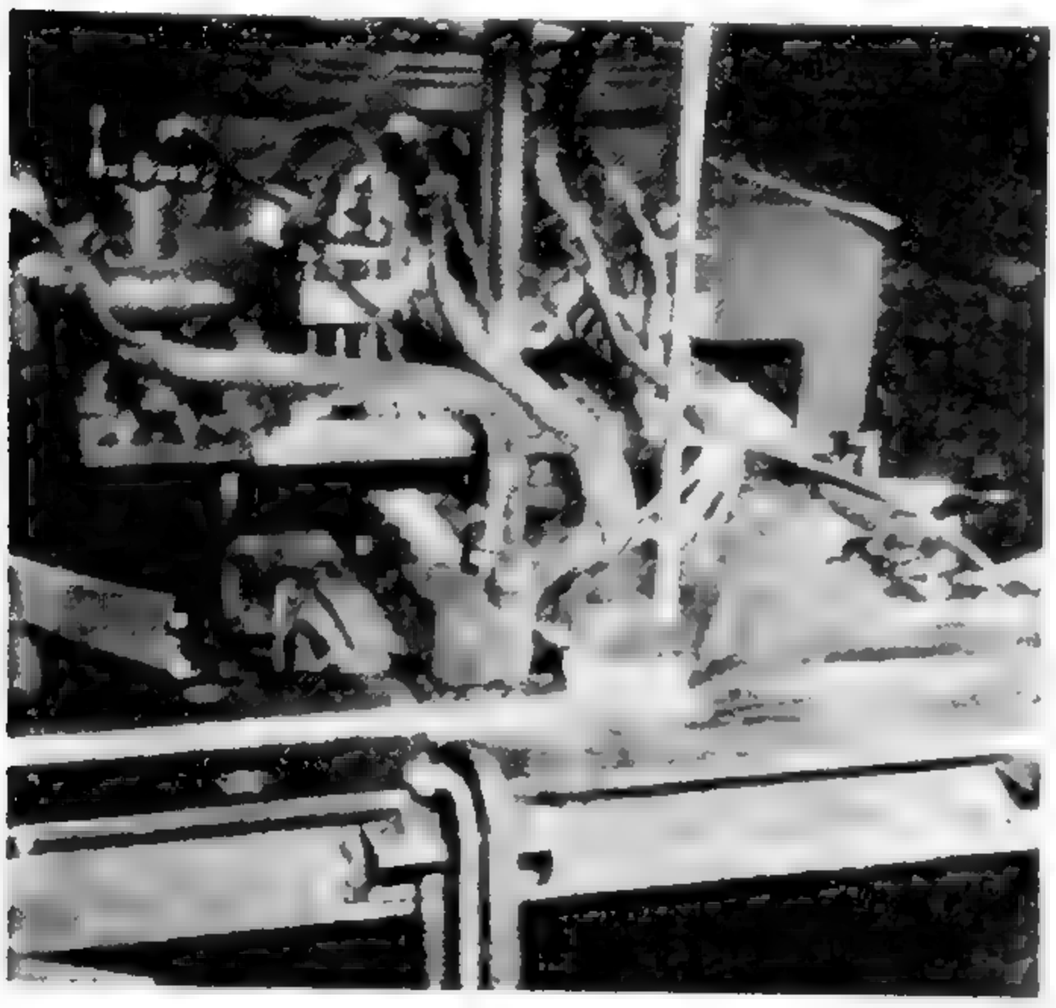

Fig. 3.—Equipment for Surfacing Ensilage Cutter Blades by Semi-Automatic Gas Welding

In surfacing by oxy-acetylene welding, the welder can control the placement of the deposited metal closely or can hammer it into shape, thereby reducing finishing costs.

Arc Welding

Shielded-Metal-Arc Welding.—Surfacing by arc welding is done in the same manner and following the same principles as welding for joining by this process. The principal difference is that in surfacing, usually the added metal has a composition which is different from the base metal and, therefore, the factor of dilution must be considered. In order to minimize dilution or penetration and thus retain, as nearly as possible, the original composition of the alloy, the metal should be applied with minimum heat. In general, current, voltage, polarity and other welding conditions recommended by the manufacturers are based on this factor.

The types of electrodes and of coatings and the preferred techniques vary somewhat with the type of alloy. For convenience, these can be considered in a broader classification than that given in Chapter 38—Filler Metal.

Group A.—These include the low-alloy types of surfacing alloys which are air-hardening and produce a deposit with a hardness ranging from 25 to 60 Rockwell C. (These alloys cover Types *I-A-1* and *I-A-2* of Table 1.) The electrodes are usually of the covered type with the covering supplying alloying as well as deoxidizing and arc-stabilizing elements. For the harder types, preheating of the base metal to at least 400°F. may be necessary to avoid cracking, but in many applications the presence of small cracks is of little importance.

Group B.—These electrodes are the medium-high-alloy groups corresponding to Types *I-A-3* and *I-A-4* in Table 1. These may be either cast, in which case they will be short lengths for manual welding, or may be fabricated, in which case they may be of longer length for machine use. Both types of electrode have only a light coating for arc stabilization, as all the alloy is either in the wire or in granular form in the fabricated rod. These alloys have a lower melting point than those in Group A, hence have higher fluidity and produce a flatter surface, but must be used in the flat position only. With proper preheat, multilayer deposits can be produced free from cracks.

Group C.—These electrodes are the alloys corresponding to those in Types *I-A-5* and *I-B-1* of Table 1. They are available as cast or drawn rods, depending upon their composition and have a light, arc-stabilizing coating. With high alloy content, their melting points are lower; consequently, they are quite fluid. With the higher carbon alloys the weld metal tends to lie quite flat and should be sound and free from cracks. Generally, these electrodes are for single-pass deposits only, and preheating to 400°F. may be necessary. It is most important to minimize dilution with these alloys by applying them with lowest possible heat.

Group D.—This group comprises the alloys in Type *I-B-2* of Table 1, the austenitic manganese steels. (See Chapter 31B for further information.) These electrodes are either bare or have a light, arc-stabilizing coating. In general, the

arc characteristics of the bare electrodes are poor and this group of electrodes should be used only for welding manganese steel. Otherwise, hard intermediate composition alloys form which may lead to cracking. It is important that the base metal not be permitted to attain a temperature over 700°F. In this way transformation of the austenite into brittle structures is avoided and the properties of the base metal are retained. This metal has low-heat conductivity, hence care must be taken to use low welding heat and avoid buildup of heat in the weld zone. Peening is freely used to reduce tensile stresses and to induce some hardness in the underlying layers.

Group E.—These include the alloys in Type *II* of Table 1. The electrodes are moderately heavily coated and are for manual welding only. The avoidance of dilution is very important, hence low heat is definitely recommended. The deposits are subject to cracking, but preheating and slow cooling can satisfactorily prevent it.

Group F.—These correspond to the alloys in Type *III* of Table 1. These alloys are almost universally supplied as tube rods containing granular tungsten carbide inside the tube. The tubes may be short for manual welding or coiled for machine welding. Their arc characteristics are relatively poor, but the service requirements are seldom influenced by such matters as porosity or small cracks. The value of these alloys depends on the avoidance of melting and dissolving the granular tungsten carbide in the steel, so again minimum heat is recommended during welding. The deposits should show a considerable amount of undissolved carbide particles.

Group G.—These correspond to the nonferrous alloys in Types *IV* and *V* of Table 1. Most of the electrodes are quite heavily coated and are usually for d.c., reversed polarity welding only. The use of reversed polarity minimizes the melting of the base metal, an important factor in successful arc welding, especially with copper-base alloys. Their welding characteristics are usually satisfactory, but these electrodes are only applicable for welding in the flat position.

Machine Arc Welding.—Surfacing by machine arc welding may be by shielded metal arc, bare metal arc or submerged arc welding. For all processes, surfacing materials are available in coil form for all the types of alloys except the very hard alloys as previously indicated. In the case of the lower alloy grades and in softer, rollable materials such as the stainless steels and nickel alloys, the rods are of the solid-wire type. For depositing hard weld metal, coils are available of continuous steel tubes which contain the alloying elements needed to produce the desired weld metal composition.

Surfacing is done in the same manner and with the same apparatus used for machine welding. The deposits can be made by continuous narrow string beads, especially on a cylindrical surface, or by a series of wide weave beads on flat work. When permitted by the characteristics of the deposited metal, the surfacing layer may be built up to any desired depth or configuration by multiple layers. In this respect, the characteristics of the alloys as described for manual welding apply.

Submerged Arc Welding.—Surfacing by submerged arc welding is done very satisfactorily with the same apparatus and materials used for welding (see Chapter 13). The technique for surfacing varies from that for welding only to meet the demands for minimum dilution and to avoid cracking of hard deposits. There are several means available for minimizing these. The first is the use of d.c., straight polarity, combined with higher voltage (about 40 volts) and low-current density. Slow welding speed with appropriate welding technique also minimizes dilution. Other types of power are widely used but only when dilution is not the dominant factor or when it is minimized in other ways. For instance, d.c. reverse polarity power has been found to be very beneficial in reducing the tendency to cracking of some of the harder alloys.

Under the recommended conditions of power but at the usual welding speeds, the weld metal may be diluted appreciably by the base metal. Therefore, if surfacing is done under normal welding conditions, it is necessary to apply three or more layers of weld deposit before the deposited metal will be free from the effect of the base metal composition. This holds, especially, when there is a wide difference in composition between the surfacing and base metals.

There are two ready methods of avoiding this condition. In the first, the composition of the welding rod is chosen to compensate for the anticipated dilution

by the base metal. This can be quite readily done, especially when the surfacing metal is of the low-alloy steels, such as Types *I-A-1, I-A-2 and I-A-3.* In such cases, alloys from the next higher type would probably be satisfactory. In the second method, the first layer is applied at a slower rate of travel; i.e., in the order of 4 to 8 in. per minute. This procedure reduces dilution to the order of 10 to 15%, hence, retains the essential characteristics of the deposited metal. Subsequent layers may then be applied by normal techniques. The choice of welding composition or flux is important as some of them lead to an increase in manganese and silicon contents and some preserve the composition of the metal more nearly constant than others. The advice of suppliers should be sought for this type of data.

Preheat is important in minimizing cracking in the hard and hardenable steels and alloys. For applying the hardenable low-alloy steels, Types *I-A-2* and *I-A-3*, the base metal should be preheated to about 500°F. and maintained at this temperature for the complete time of application. (On large jobs it may be necessary to put the work in a furnace overnight if not completed.) At this temperature, the formation of martensite is retarded, and therefore cracking is minimized. The desired hardening will then develop uniformly upon subsequent cooling. It may be necessary in large, continuous deposits to cool the assembly in order to avoid an excessive rise in temperature due to continuous high heat input. Such cooling can be done quite satisfactorily with an air blast.

Inert-Gas Metal-Arc Welding.—Surfacing by inert-gas metal-arc welding is done in much the same way as welding by this process except for slight modifications to reduce dilution (see Chapter 12). By proper application of the process, the dilution factor will be somewhat higher than is obtainable with gas welding, but much lower than is produced by shielded-metal-arc welding. The rate of deposition is higher but the distortion produced is less than in gas welding.

The process is used mostly with bare rods but has been used with some coated rods. The alloys in Type *II* and some alloys in Type *I-B-1* of Table 1 have been successfully applied. Likewise, the aluminum bronzes, Type *IV-C*, have been applied quite satisfactorily and practically all the high-nickel alloys, such as Types *V-B* and *V-C*, are easily applied with this process.

Because of the essentially neutral or non-oxidizing character of the atmosphere in the weld zone, the process is applicable to the production of such combinations as aluminum bronze on copper, or silicon bronze on steel.

The essential items in welding technique that minimize dilution and which therefore should be observed in application of single-layer deposits or in the first layer of moderately thick deposits are: (1) backhand welding, (2) a.c. welding power and (3) use of about 12 liters per min. of inert gas.

For application of subsequent layers or when dilution is unimportant, faster procedures of welding, such as forehand welding and d.c., straight polarity should be used. These welding conditions require only about 6 liters per min. of inert gas.

Special Merits of Arc-Welding.—The special merits of arc welding by either the shielded metal-arc or submerged arc processes lie mostly in the high rates of deposition attainable, flexibility of application and ease of mechanization. The rate of deposition can readily be as high as 25 lb. per. hr. by the submerged arc process, and for those alloys which are available in coil form, this rate of deposition can be maintained for long periods of time. It is, therefore, entirely feasible to surface large areas or to apply deep layers of surfacing materials by multiple passes. Much surfacing of this type is done. Likewise, arc welding is especially applicable to the localized surfacing of large or heavy members where excess time or heat would be required by the gas welding processes. Short pads can thus be built upon parts such as dipper teeth (see Fig. 4) where it is desired not to affect the remaining base metal any more than is necessary. Figure 5 shows a typical submerged arc welding application.

SURFACING METHODS

Materials Normally Surfaced

Surfacing is applied to many base materials for purposes of preservation or greater wear; the selection of filler metal is usually on the basis of the specific

wear or corrosion conditions to be encountered. The following section offers pointers on the applicability of surfacing to typical base metals.

Low- and Medium-Carbon Steels.—All plain carbon steels having up to 0.50% carbon can be surfaced under normal conditions by any of the several welding processes and with any of the hard or hardenable ferrous or nonferrous alloys. over 0.50% carbon can be quite readily surfaced by gas welding using the several surfacing materials without unusual precautions. This is because, with gas welding, the base metal is automatically preheated, and cracking and hardening are thereby minimized. However, with any of the arc-welding processes it is usually advisable to preheat to temperatures of 300 to 600°F. This will prevent cracking

Fig. 4.—Surfacing Dipper Teeth by Manual Shielded Metal-Arc Welding

In fact, SAE 1040 steel is a frequent choice as a base for surfacing. An important precaution to be observed is that in surfacing with bronze or brass alloys care should be taken to avoid melting or overheating the base metal, which will promote penetration of the bronze or brass into the base metal.

High-Carbon Steels.—Steels containing due to sudden heating of hardened parts and will avoid hardening of the heat-affected zone during cooling. These general precautions apply regardless of the type of surfacing material being applied.

Low-Alloy Steels.—Surfacing alloys can be applied to low-alloy steels in much the same manner as to plain-carbon steels of the same hardenability, provided

the steel is not in the hardened state. If it is in the hardened state, it should first be annealed. In a few cases, depending upon the composition of the base metal, heat treatment is required after welding.

High-Speed Steels.—Surfacing of this group of steels is seldom done and is not generally recommended. They can be surfaced with some hard, steel-base alloys without difficulty so far as technique is concerned, but shrinkage cracks and strain checks render the surfaced piece valueless in a good many instances despite heat treatment. Usually there is little need for surfacing high-speed steels as surfaced parts of low-alloy steel should be equally satisfactory.

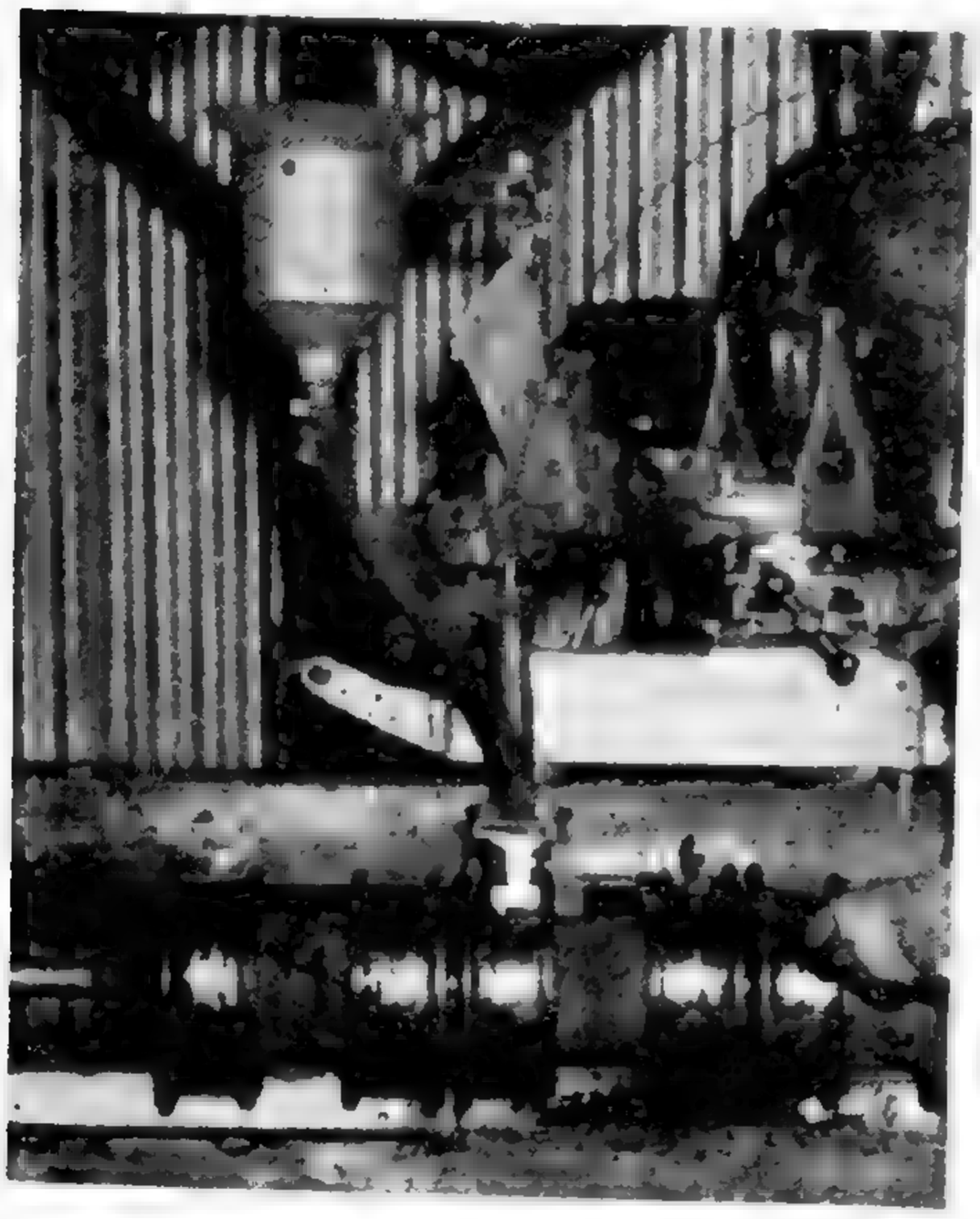

Fig. 5.—Surfacing Tractor Rollers by Submerged Arc Welding

Stainless Steels.—Stainless steels, including the high-chromium steels and the 18–8 chrome-nickel steels, can be surfaced quite satisfactorily with most of the alloys having appropriate melting points. However, a knowledge of the physical properties of the particular type of stainless steel is necessary, otherwise difficulty may be experienced due to brittleness or lessened corrosion resistance. The usual precautions due to the high coefficient of expansion of the 18–8 steels should be observed.

Manganese (Hadfield) Steel.—This steel is surfaced by the shielded metal-arc welding process alone, and then usually with the austenitic, work-hardening type of alloys, or with alloys which will bond readily with this base metal.

Gray and Alloy Cast Irons.—Special care is needed for the application of steel-base surfacing alloys to cast iron. The lower-melting-point alloys and most of the austenitic alloys are quite readily applied to cast iron using proper precautions to avoid cracking before and after welding. Type *II* alloys are also readily applicable to cast iron, although a flux may be useful in dissolving the surface coating on the cast iron. Likewise, the nickel and copper alloys are readily applicable. The bronze surfacing of cast iron is easily accomplished by following the general principles of braze welding.

White Cast Iron and Malleable Iron.—There is little success in surfacing white iron because the welding heat, even for braze welding, materially alters the properties of the underlying metal, and the original condition cannot be restored. However, malleable iron can be surfaced in the same manner as cast iron. Bronze surfacing produces the least detrimental effect on the underlying base metal as it causes only a slight solution of the carbon.

Copper, Brass and Bronze.—These alloys are difficult to surface with any of the ferrous or high-alloy, nonferrous types of surfacing metals because of the low melting points of the base metal. If it is accomplished, inordinate amounts of base metal are melted to the detriment of the weld deposit. However, the brass or bronze surfacing alloys and some nickel alloys can be applied very readily without any unusual procedures. Fluxes are usually needed for the production of sound welds.

Factors Affecting the Welding Quality

The requirements in regard to the quality of deposit needed vary considerably with the service to which the part is to be exposed. For instance, for surfaced valve seats, the deposited metal must be entirely free from cracks or pinholes, but on dredger teeth porosity is of little importance. However, the quality of most deposits can be quite high and the follow-

ing notes should help in producing the best-quality deposits.

Steel Base Surfacing Alloy (Types I-A-1, I-A-2 and I-A-3).—There is little difficulty with cracking with these alloys, and the deposit by either gas or electric welding should be completely sound. Any porosity will be the result of overheating, unclean base metal or otherwise improper applications. Some cracking may develop with the higher carbon grades of these alloys but this can be effectively prevented by moderate preheating.

High-Alloy Cast Steel and Cast Iron (Types I-A-4 and I-C-1 and I-C-2).—Deposits with these alloys are subject to cracking and porosity, but both can be avoided. Adequate preheat will help to avoid cracking, but, in some instances, the differences in coefficients of expansion may be so great that cracking develops anyway. Under such circumstances, a different choice of surfacing metal will have to be made, or an intervening layer of austenitic alloy may be employed. Care may be necessary to avoid cracking during any subsequent heat treatment. Porosity should be preventable and is usually caused by unclean base metal or improper welding conditions.

Cobalt-Base (Type II-A).—Generally for relatively simple parts, no special precautions are needed in applying these alloys, but for larger assemblies, especially where extended areas are to be coated, preheating is necessary to avoid cracking. With gas welding, the preheat associated with the flames is usually adequate, but relatively high preheat will be needed for application by arc welding. Deposits made with these alloys should, and can, be entirely free from porosity as in many applications resistance to corrosion is of great importance. Any porosity that occurs is often a result of unclean or oxidized base metal, overheating or excessive melting of the base metal. In some cases in gas welding a flux may be beneficial, but in general the flowing characteristics developed by the reducing flame should yield sound weld metal. These metals have a high strength at high temperatures hence may cause distortion or shrinkage of the final assembly. For cylindrical sections it may be necessary to anticipate this by starting out with a larger diameter section. For long, narrow deposits on bar stock, for instance, prebending in the reverse direction to the amount of 1/8 in. per ft. has been found to be a suitable corrective for this condition (see Fig. 6). The contraction of the surfacing metal which is applied to the convex surface causes the final part to be straight. The amount of prebending is determined by experiment.

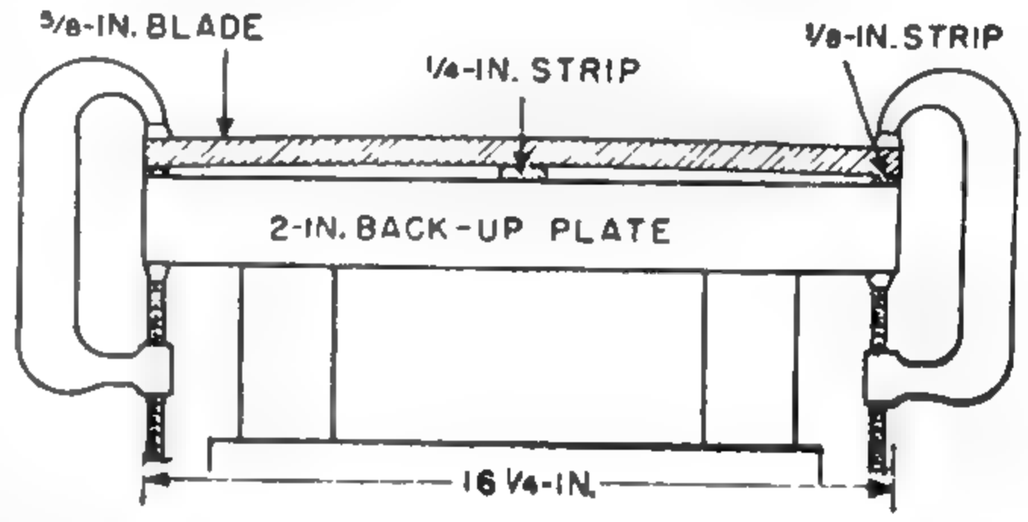

Fig. 6.—Suggested Method of Prebending and Clamping Long Strips for Surfacing

Hard Carbides.—Usually the presence of porosity in deposits of this type of surfacing alloy is not important, but it can be minimized by making the deposits under the most favorable conditions with respect to depth of weld and avoidance of overheating. The principal difficulty to overcome is excessive solution of the hard carbides in the matrix alloy. It is essential to retain them, whether as particles or as cast inserts, in as nearly the same condition as possible in the deposit as before welding. Excessive heat or overpuddling of the weld tends to dissolve these metals into the base material. This is especially true in the case of shielded metal-arc or submerged arc welding where the temperature of the molten metal is quite high. Consequently, for minimum solution, gas welding is most frequently used. Another trouble arises with the tube or granular type rods due to the greater density of the carbides. They tend to settle to the bottom of the weld deposit, thereby leaving a soft top layer. This is best avoided by applying these materials in shallow layers. This greatly minimizes segregation and gives more satisfactory service.

Copper-Base Alloys.—Very little difficulty is encountered in producing deposits of excellent quality in gas-welded deposits using the so-called low-fuming bronze rods. The principal point to watch is to avoid overheating as this may cause porosity and penetration of the bronze into steel base metals. Cast iron is not

thus affected. No trouble with cracking should occur.

For arc welding, the aluminum bronzes are used quite extensively, and deposits made with these alloys will have satisfactory quality if the proper welding conditions are used. Again, avoidance of melting the base metal is necessary for high quality.

Heat Treatment

The response of the surfacing layer to heat treatment obviously depends on the composition of the material but, in general, heat treatment for the purpose of increasing hardness is applicable only to deposits made with alloys of the hardenable steels, Types *I-A-1, I-A-2* and *I-A-3.* So far as has been determined, weld deposits respond to heat treatment in the same manner as rolled or cast metals of the same compositions. Therefore, if the composition of the deposited metal (not the welding rod or electrode) is known, its response to heat treatment can be readily found by reference to Jominy tests or isothermal transformation curves for steels of similar composition. The precaution of determining the composition of the weld deposit should be observed as there may be some change in composition during welding, either by loss or gain in carbon or the alloying elements, which would change appreciably the hardenability of the metal.

On this basis, therefore, surfacing layers of hardenable steel may be heat treated by furnace treatment, spot or continuous flame-hardening.

Finishing

In many instances, the condition in which the deposited metal is left at the end of the welding operation has a very important bearing on the cost of the surfacing operation. For some parts, such as tractor grousers, dimensions are of little importance, but on many others it is highly desirable that the deposited metal in the as-welded condition should be close to the desired final dimensions. Due to the very nature of the surfacing layer, removal by machining or grinding may be difficult and expensive.

Of the welding processes available, there are definite advantages to depositing thin surfacing layers by oxy-acetylene welding because not only can the weld metal be laid down smoothly and, if necessary, in quite thin layers out to an edge, but the addition of weld metal can be stopped at will and the deposited metal, if forgeable at high temperature, can be hammered to shape. This procedure is applicable to a number of the hard-surfacing alloys and is of great practical value, especially on deposits near an edge or corner. The current practice of building up railroad rail ends is an excellent example of the practical value of this procedure for reducing the cost of finishing.

Another method, applicable primarily to the hardest deposits, is known as *hot-filing.* When a deposit of one of these alloys is heated to within 50 to 300°F. of its melting point, it may be scraped off in thin layers with a coarse file or similar instrument until the deposit has been brought down to its desired dimension. Final grinding will usually be necessary to finish these deposits as the surface thus produced is quite rough.

Many surfaced parts are finished by grinding or machining. The usual precautions in regard to machining speeds, type and setting of tool should be observed for the particular alloy used. For the harder types of surfacing metals, grinding or machining with a sintered tungsten carbide tool must be resorted to for best results. The recommendations of grinding wheel manufacturers should be followed in determining the type of wheel and speed for any alloy.

Inspection

Obviously, the type of inspection applied depends upon the quality desired in the deposit. Of the various inspection methods, aside from visual, the hardness test is probably the most widely used. This may be done with a relatively simple tool like a file or portable instrument of measuring hardness or more detailed and exact testing may be done in a laboratory. The primary advantage of the hardness test is that it indicates the amount of dilution that occurred during welding. For a welding rod of given composition, the deposit should have a hardness that does not vary outside a certain range. If the deposited weld metal has a hardness outside this range and the variation cannot be directly attributed to other factors such as cooling rate, it is presumptive evidence that excessive dilution, overheating or some other important deviation from good practice occurred. Thus, this

test provides a relatively quick check on the degree to which the welding conditions approach the ideal.

Soundness and freedom from cracking can be readily determined by magnetic particle or fluorescent oil inspection. These methods are especially useful for parts such as valve seats where freedom from minor imperfections is essential.

Etching with a suitable mild agent is frequently useful for delineating the contour of the deposited metal. This should give information on the extent of the area covered and how well it conformed to the coverage desired. Sections obtained through deposits can be similarly etched to show the depth and distribution of the surfacing metal. For steel base deposits, a 10% solution of ammonium persulfate in water rubbed on the filed or ground surface will be a satisfactory etch. For brass and bronze a 10% solution of nitric acid will serve very well.

COMMON APPLICATIONS

It is impractical to enumerate or list all the applications where surfacing has been advantageously used. However, it can be generally accepted that the principles of surfacing have not been applied to their optimum extent, and that the advantages which the process offers have not yet been fully realized by the designer and user in many engineering fields. Therefore, the following examples have been given, not with the purpose of indicating the extent of use of the process, but as guides concerning the range of parts or structures in which surfacing either has been profitably employed or is a prerequisite to successful service. These examples have been grouped in respect to the broad general types of service and have been taken from all branches of engineering. The types of alloys that would be serviceable for such applications are suggested on the basis of experience and are not necessarily complete. Subsequent experience might enlarge or limit the utility of any one type of alloy.

I. Surfaces subject to earth and other abrasion without heavy impact: drag scraper and ditcher teeth, harrow teeth, and plow shares, ash plows, shovels, pipe line elbows and Y's, sand slinger cups, exhaust fans, chutes, tractor grousers, rotary oil well drill bits, stoker screws, tractor treads, roller bits, sand plows, tool joints. (Types *I-A-2d; I-A-3c; I-A-4c* and *I-A-4d; I-C-1* and *I-C-2; II-A* and *II-B; III-A, III-B,* and *III-C.*)

II. Surfaces subject to abrasion with heavy impact: clam shell teeth, coke and metal crushing segments and rolls, swing hammers, drag scraper teeth, bulldozer tips, rabble discs, baffle plates, roll crusher plates and teeth, dipper teeth, tamping bars, crushing and pulverizing equipment, crusher cones. (Types *I-A-3b; I-A-4b* and *I-A-4c; I-B-1* and *I-B-2, I-C-1* and *I-C-2; II-A; III-A, III-B* and *III-C.*)

III. Rolling and sliding metal-to-metal contact: sprocket teeth, shafts, sleeves and bushings, collars, lathe centers, ball joints, rolling mill guides, gear cones, wobblers, clutch plates, roll surfaces, railroad rails and frogs, piston rods, thrust washers, locomotive throttle guides, car retarders, wire straightening rolls, crane wheels. (Types *I-A-1b* and *I-A-1c; I-A-2b* and *I-A-2c; I-A-3a* and *I-A-3b; I-A-4a* and *I-A-4b; I-B-2; I-C-1; I-C-2a, I-C-2b* and *I-C-2c; II-A* and *II-B; III-A; IV-A, IV-B* and *IV-C;* and *V-C.*)

IV. Surfaces subject to erosion, corrosion, wire drawing, etc.: valves and valve seats for steam, water, oil, etc., valve stems, sand-blast nozzles, steam cylinder pistons, hot oil pump pistons, vegetable oil extractors, pump shafts and sleeves of all types, needle valves. (Types *I-B-1a* and *I-B-1b; I-C-1; I-C-2a, I-C-2b* and *I-C-2c; II-A* and *II-B; IV-A, IV-B* and *IV-C; V-A, V-B* and *V-C.*)

V. Cold cutting edges of all sorts: ensilage cutters used on farms to shearing and trimming dies in a steel mill. (Types *I-A-3* and *I-A-4; I-C-1* and *I-C-2; II-A* and *II-B; III-A, III-B* and *III-C.*)

VI. Surfaces subject to hot service: steel mill guides, hot shears, aircraft valve seats, hot-drawing dies, deep-drawing centers, forming and upsetting dies, manipulator tongs. (Types *I-A-3c; I-A-4c* and *I-A-4d; I-A-5; I-C-1* and *I-C-2; II-A* and *II-B; V-B* and *V-C.*)

B. METALLIZING

FUNDAMENTALS OF PROCESS

Definition

Metallizing is a broad term for the application of metallic coatings to various surfaces by spraying with finely divided particles of molten metal. This discussion

is limited to the spraying of metal onto metal. Several basic types of metal spray guns have been developed, but the most widely used is the wire-type gun. With this gun, metal in the form of wire is introduced into an oxy-fuel gas flame surrounded by a blast of high-velocity air, and small particles of molten metal are projected against the work. Almost any metal or alloy may be applied, and coatings may be built up to an appreciable thickness.

Metal deposited by this process resembles the base wire chemically, but the physical properties are quite different from those of the original metal. The structure is not homogeneous, and photomicrographs show each particle to be at least partly surrounded by a fine oxide film (see Fig. 7). Tensile strength is quite

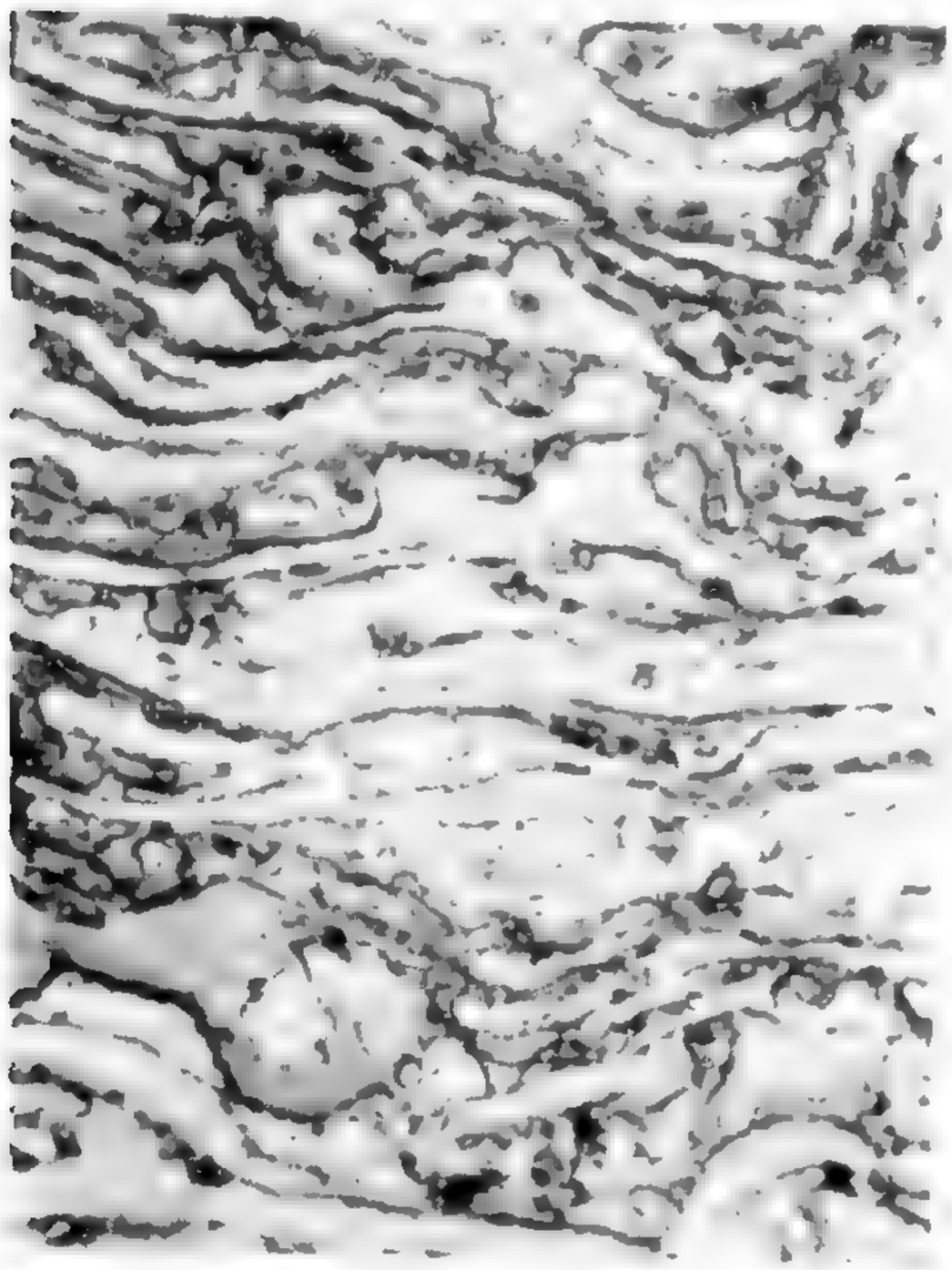

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Fig. 7.—Cross Section of Sprayed Low-Carbon Steel

high with some sprayed metals, but ductility is low, and all coatings are porous to some extent. Sprayed metals bear some resemblance to the stronger types of sintered metals, and as with the latter, they should be considered as separate and distinct metallurgical materials.

Although metallizing is widely used for corrosion-resistant and production purposes, its greatest use in this country is in the machine element field. Worn or mismachined parts are restored to size by applying metal selected for the particular service involved. Sprayed coatings may be applied for this type of work

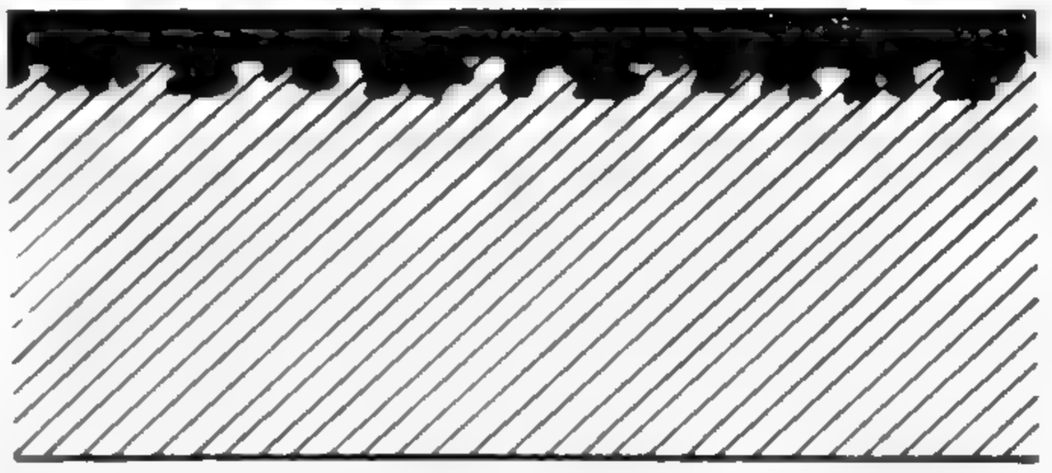

Fig. 8.—Surface Preparation by Grit Blasting

without overheating and distortion of the base metal.

Principles of Operation

The metallizing process is divided into two distinct parts. The first part is the preparation of surfaces to receive the metal and the second part, the application of the metal.

Preparation of Surfaces.—With but one exception, the bonding of sprayed metal is accomplished mechanically, since there is no fusion between the sprayed metal and the base. Therefore, the base must be prepared to mechanically bond with the metal being applied. One of several types of preparation, as discussed later, may be used, but all employ some means of dovetail keying. Figure 8 illustrates the surface preparation obtained by blasting with crushed steel grit.

The most commonly used method for shaft buildup provides a dovetail thread from end to end of the surface to be coated. Since the sprayed metal is in a molten or plastic state when it impinges on the surface, it is forced under all projections and immediately solidifies.

The one method of surface preparation which does not involve mechanical bonding employs a special molybdenum alloy which is sprayed onto a clean surface which may be smooth or roughened. The special material forms a metallurgical bond with the base as shown in Fig. 9. This metal is used for a complete buildup or as a bonding coating only, with the required metal being sprayed directly onto it. Each of the more common methods is described briefly below:

1. Groove and Rotary Roughening Tool

Method: A rotary shaft preparing tool, which is used over a thread or over a series of grooves, produces an excellent bonding surface. This tool may be used with good results on any metal which is readily machinable. The surface obtained by this method is shown in Fig. 10.

2. Rough Threading Method: Cylindrical surfaces such as shafts, rolls, etc., may sometimes be prepared by rough threading. The procedure consists of chasing a thread with a specially ground tool, in such a manner as to tear apart the surface and produce a rough, ragged thread. Rough threading can only be used on certain types of material and the operation is critical. A thread which is subsequently blasted with steel grit, however, produces a very adherent surface. The surface obtained by this method is shown in Fig. 11.

3. Metallic Spray Bonding Method: Certain alloys high in molybdenum may be sprayed directly on smooth surfaces

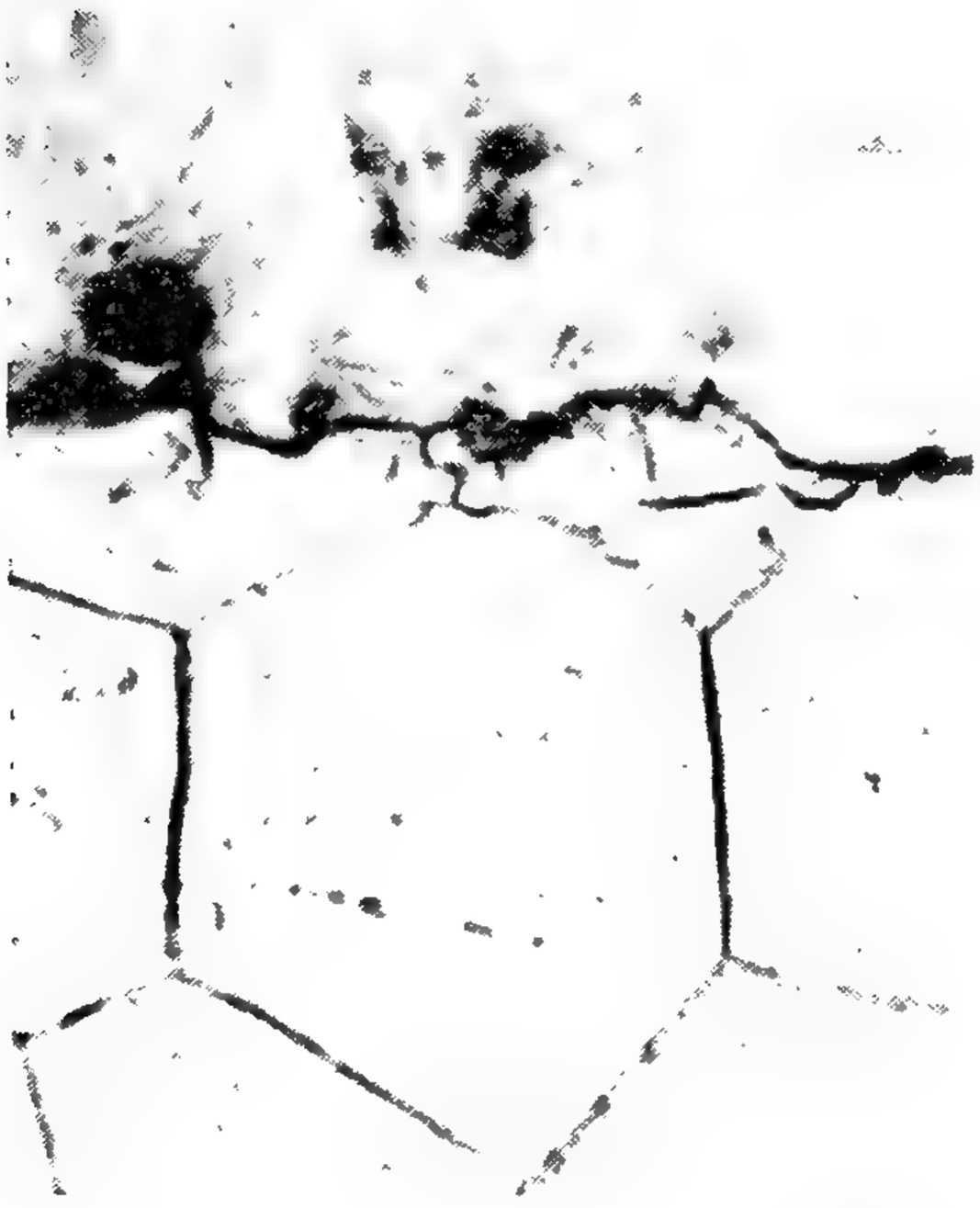

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Fig. 9.—Surface Bonding with Metallic Spray Bond Method

of steel and other alloys, and bond to such surfaces by fusion rather than by mechanical interlocking. Wire suitable for this purpose is available. The use of this material as a bonding coat eliminates elaborate surface preparation, and presents many advantages in the scope and technique of metal spraying. The surface obtained by this method is shown in Fig. 12.

4. Electric Bond Method: The electric bond method is used to deposit on the surface a bonding coat of nickel alloy. This is accomplished by using a transformer having the proper current characteristics, and stroking the work with nickel-alloy electrodes. Surfaces prepared by this method are quite rough and produce a strong bond, but are generally unsuitable for thin, uniform coatings. The surface obtained by this method is shown in Fig. 13.

5. Blasting Method: Probably the oldest method of surface preparation is abrasive blasting, using either a force-feed or suction-feed blast generator or a centrifugal blasting machine. A medium grade of clean sharp sand is suitable as a preparation for thin coatings (up to 0.010 in. thick) of low-melting-point metals. Steel grit is used in preparing surfaces for heavy coatings, or for the application of metals with high melting points. Aluminum-oxide abrasive is quite widely used, but like steel grit, its use is limited, because of cost, to work which may be done in a blast room or cabinet. All outside structures, where the abrasive cannot be recovered, are blasted with sand, and blasting is the only economically feasible method of preparing large areas for metallizing. The surface obtained by this method is shown in Fig. 14.

Application of the Metal.—Application of the sprayed metal is accomplished with a metallizing gun which feeds the metal into an oxy-fuel gas flame (or other source of heat), atomizes it into very fine molten particles and projects it onto the surface at high velocity, by means of compressed air. The metal is normally applied in thin layers, less than 0.010 in. thick. Each layer bonds to the preceding layer in the same manner that each particle bonds to another. The nature of the bond is not fully understood, but there is strong evidence to support the theory that the oxide-metal affinity plays an important part in bond between particles.

Metallizing applications may be divided into two broad classes—machine element work and corrosion preventive work. The former class is generally a machine operation, while the latter is, as a rule, a manual operation similar to paint spraying. The

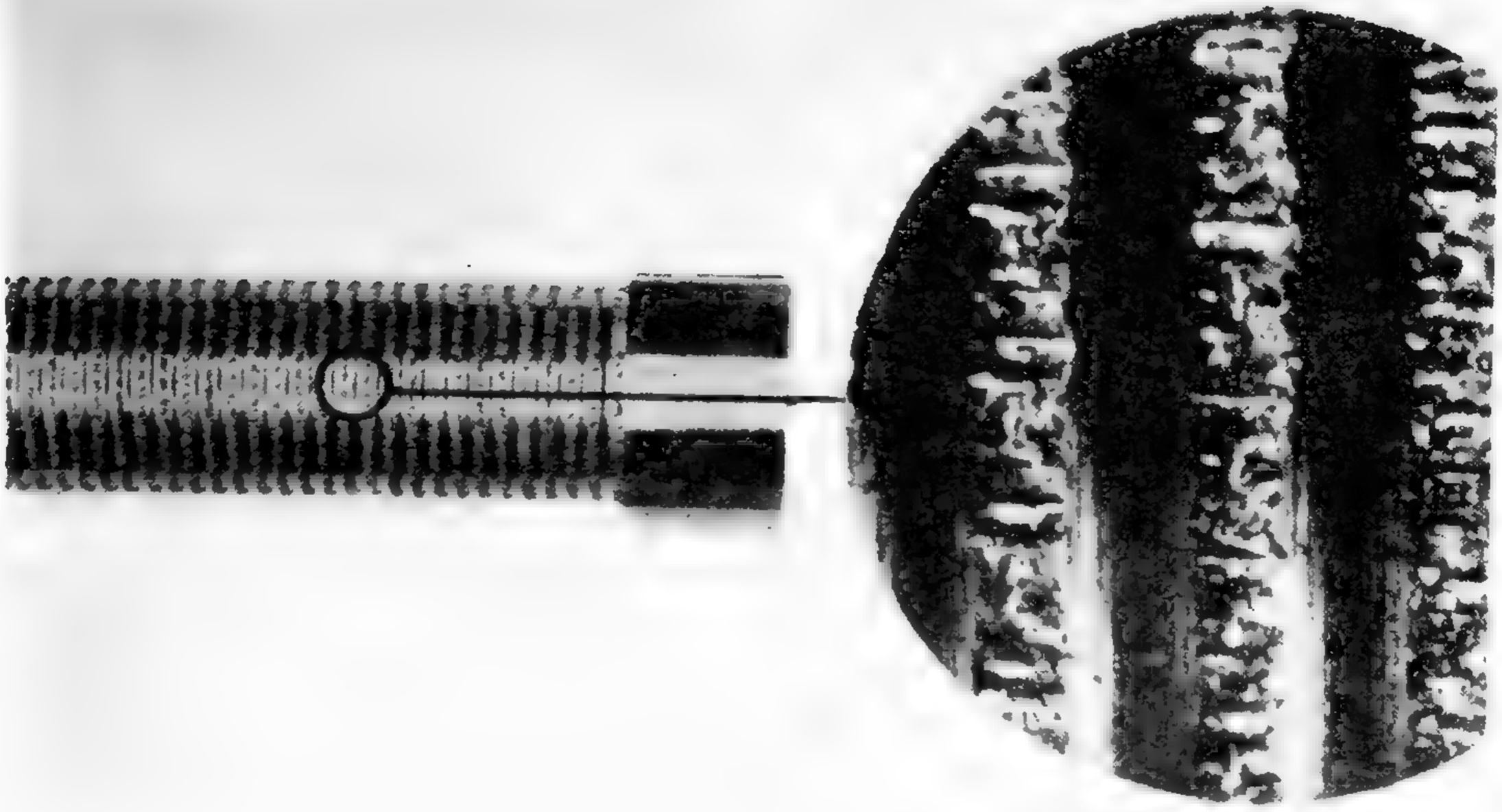


Fig. 10.—Surface Preparation by Groove and Rotary Roughening Tool Method 10 ×

technique of applying the metal is similar for all types of guns.

For machine element application, the work is generally set up in a lathe or other machine tool, and the gun mounted on the tool post so as to traverse the work automatically. The distance from the gun nozzle to the work surface varies between 4 and 10 in., depending on the type of gun and the metal being sprayed. The surface speed of the work ranges from 25 to 200 ft. per minute. The traverse

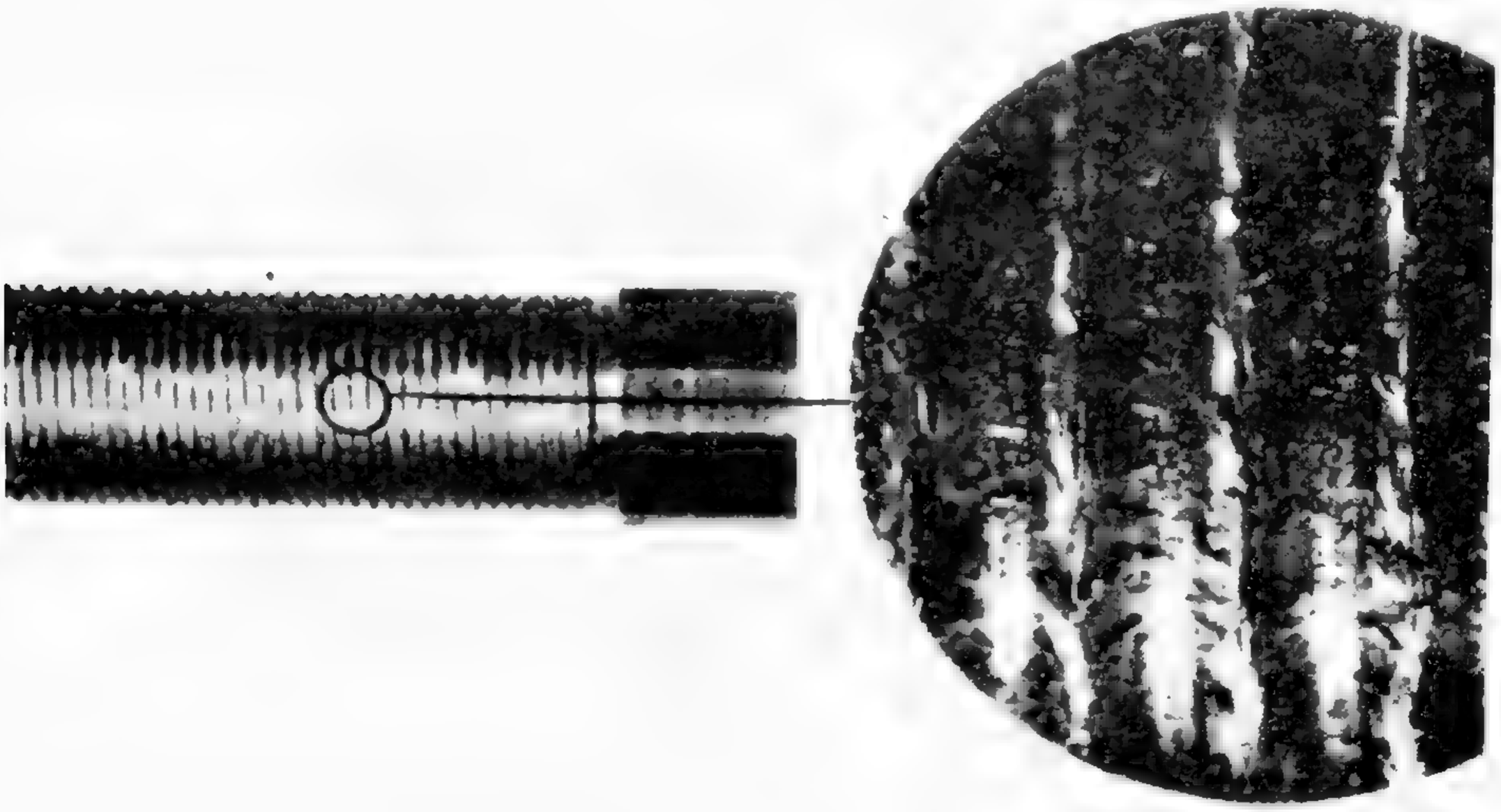
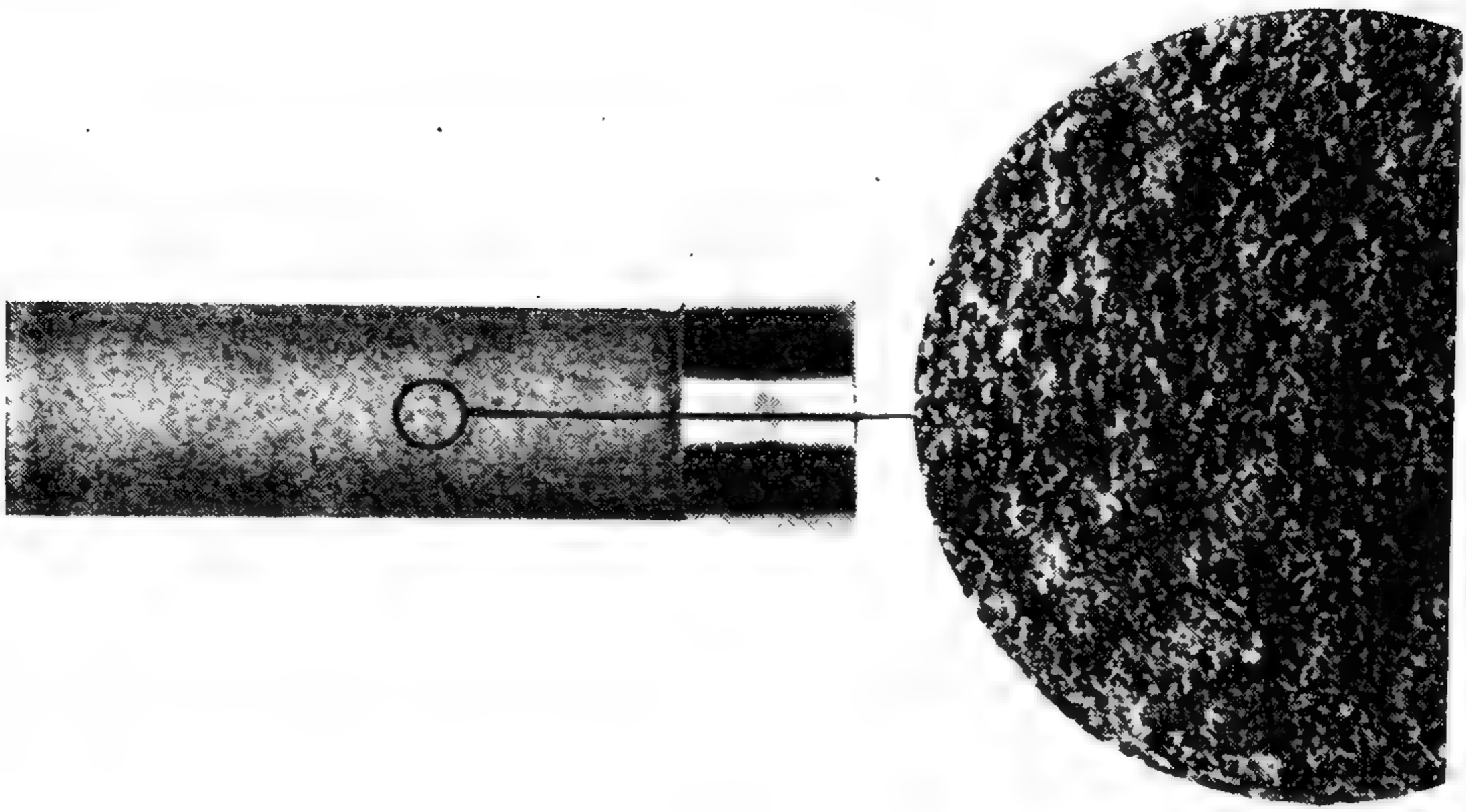


Fig. 11.—Surface Preparation by Rough Threading Method 10 ×



10 ×

Fig. 12.—Surface Preparation by Metallic Spray Bond Method

is usually fast enough to deposit only a few thousandths of metal per pass.

It is possible to apply heavy coatings in a single pass by using a slow traverse. This method is favored by some users, and is satisfactory with certain metals. The coating may also be built up in a number of fast passes. Coatings applied in a few passes, at medium traverse speeds, may have laminar or stratified structures. The multiple-pass method is generally recommended because it is safer than the single-pass method.

Flat surfaces and large areas are usually

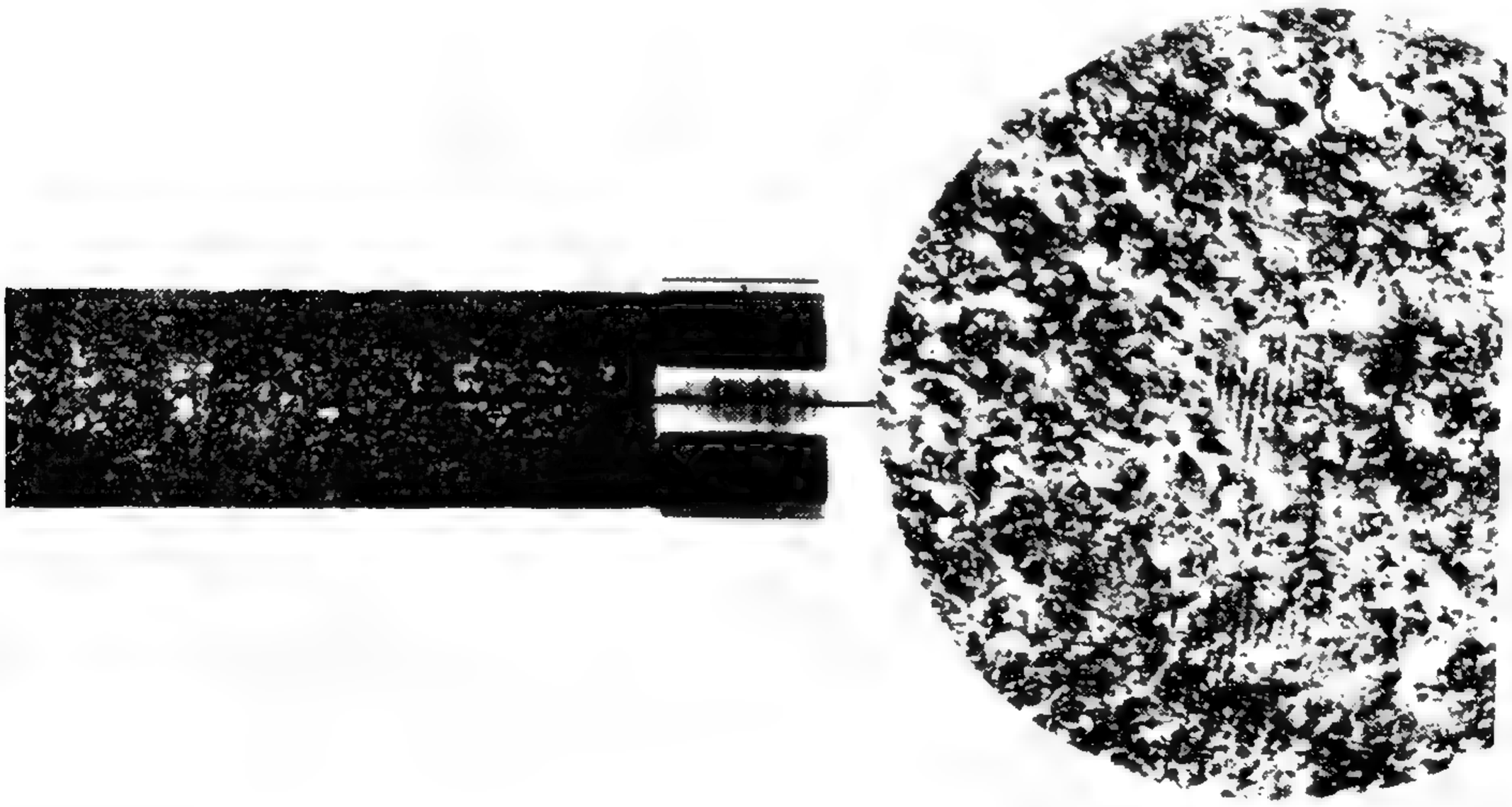


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Fig. 13.—Surface Preparation by Electric Bond Method

coated manually in a manner similar to paint spraying. Thickness may be controlled by calculating the area, and weighing out the required amount of wire. Ordinarily, the surface will be traversed three to six times, usually with alternate vertical and horizontal passes of the gun. The finished coating can be checked with an electric thickness gage immediately after spraying, and if any thin sections are found more metal can be added.

Production spraying of small parts may be done in tumbling barrels. This method results in very uniform deposits, and a minimum of metal loss. The tumbling action also tends to improve the finish. Small hardware, costume jewelry, etc., may be economically processed in this manner.

The Spraywеld Process.—This process differs from regular metallizing applications in that the sprayed deposit is subsequently fused to the base metal. Thus, the metallizing gun is simply used to preplace the required amount of surfacing material. After fusing, using one or more acetylene torches, the surfacing alloy is homogeneous, free from segregation, of uniform thickness and smooth. The thickness may be controlled within 0.001 to 0.003 in. utilizing this method.

In this process, the surface is first prepared in the same manner as for other metallizing work. The surfacing alloy is then applied either with a powder gun, or with a wire gun. For depositing hard alloys, a plastic-bonded wire or rod is available. In this case, the plastic constituents are completely volatilized during the spraying operation. The coating is built up to the required thickness, plus an allowance of 25% for shrinkage during the fusing operation.

The alloy used for this process possesses excellent resistance to oxidation, a wide range of plasticity (1850 to 2050°F.) and the ability to fuse to a wide variety of metals. Hardness of surfaces produced by this process is Rockwell C58 to C61, and in many cases such surfaces will outwear hardened steel in the ratio of ten to one.

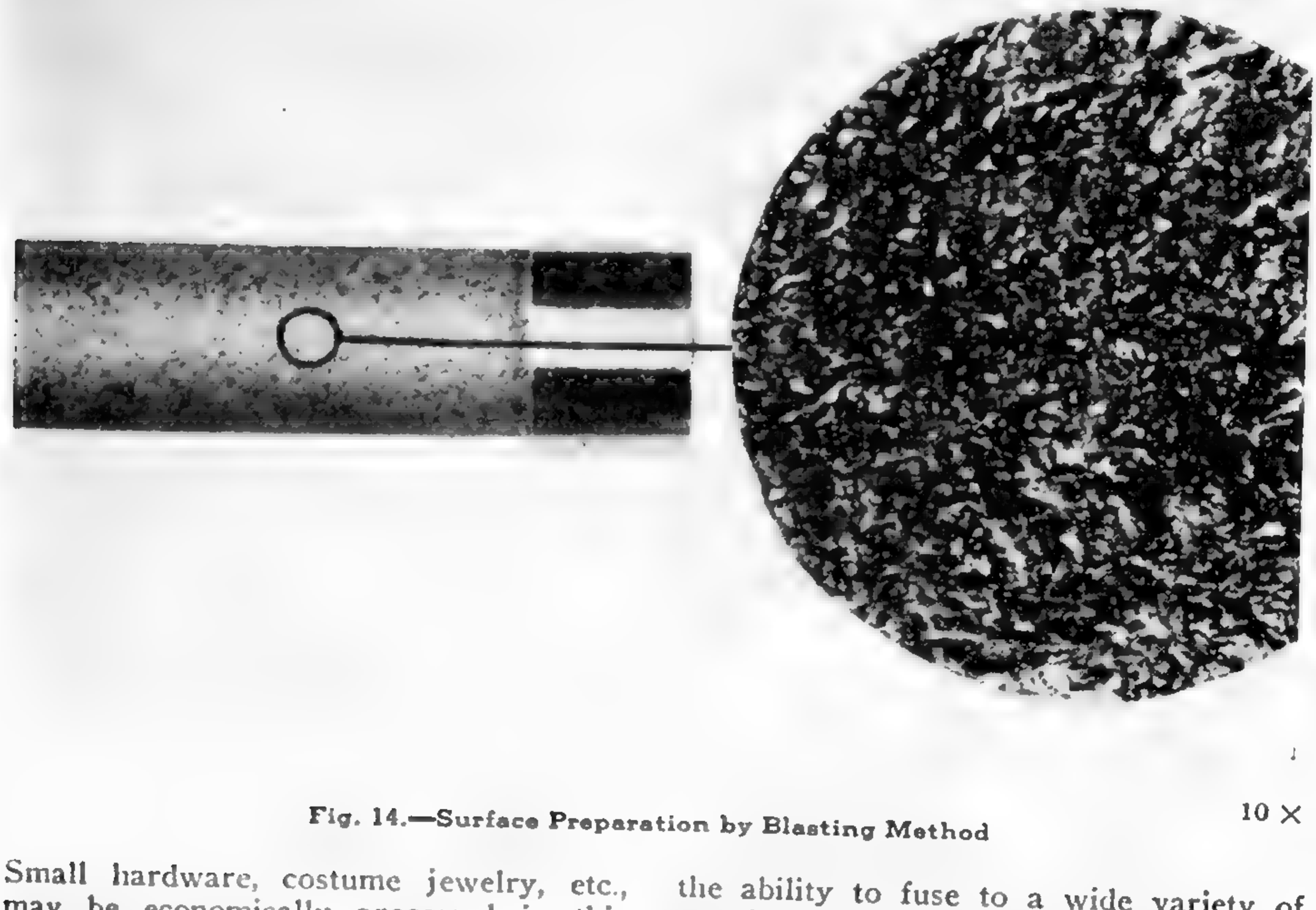


Fig. 14.—Surface Preparation by Blasting Method 10 ×

Finishing Sprayed Metals.—Sprayed metals may be finished by grinding, machining, wire-brushing, honing, lapping or polishing. The degree of surface finish depends largely on the type of metal involved, but most of the commonly used metals and alloys do not present any difficulties if the proper technique is employed. The method of grinding tool

Table 2—Chart of Recommended Tools, Speeds and Feeds for Machining Sprayed Metals

Metal	Tool No. (See Fig. 15)	Surface Speed, Ft. per Min.	Feed, In. per Revolution
Yellow brass[a]	2	100–125	0 003–0 005
Commercial ronze[a]	3	100–125	0.003 -0.005
Aluminum[b]	3	150–200	0.003–0 005
Aluminum bronze	1	100–125	0 003–0 005
Babbitt (97% tin, 3% copper)	3	150–250	0 005–0.007
Phosphor bronze	1	100–125	0.003–0.005
Tobin bronze	1	100–125	0 003–0.005
Monel	3	100–125	0 003–0.005
Nickel	3	100–125	0.003–0.005
Copper[b]	3	100–125	0.003–0.005
Lead	3	150–250	0.005–0.010
18–8 stainless steel	3	100–125	0.003–0.005
High-chromium high-carbon stainless steel	Grind	.....	.....
0.10% carbon steel	3	75–100	0.003–0.005
0.25% carbon steel[c]	2	50–75	0.003–0.005
0.40% carbon steel[c]	2	50–75	0.003–0.005
0.80% carbon steel	Grind	.....	.....
Tin	3	150–250	0.005–0.007
Zinc	3	150–250	0.005–0.007

[a] To improve greatly the machine finish on commercial bronze and brass apply liberal coat of mixture of one part cylinder oil plus one part kerosene to the sprayed metal, with a brush, and allow to stand for 20 to 30 min before machining

[b] The same treatment applied to copper and aluminum will give a slight improvement to machine finish.

[c] The same treatment applied to steels will not improve the machine finish but will help greatly in preventing the tool from burning and permit higher machining speeds. The treatment is especially helpful in machining any hard sections that may be encountered at the ends of the sprayed section or in corners.

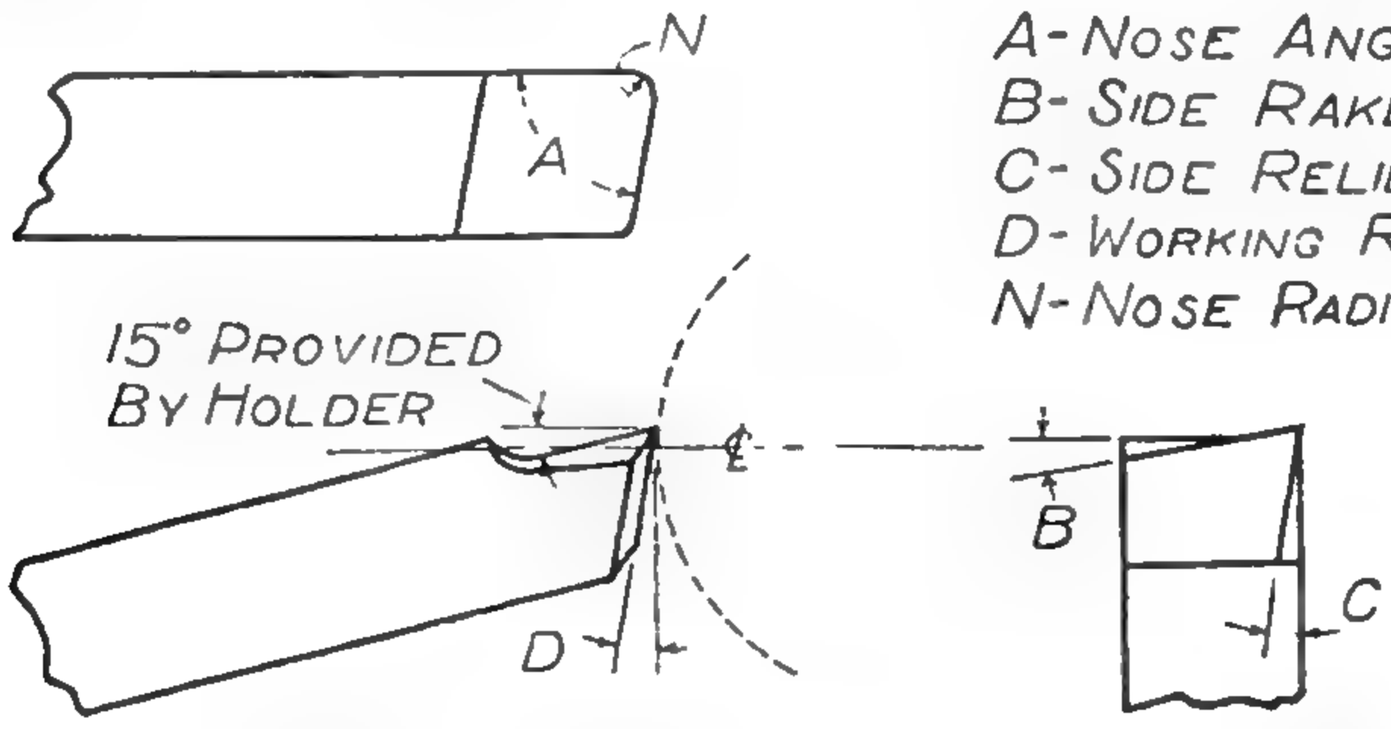
NOTE: Do not use this treatment on stainless steel, nickel, Monel, aluminum bronze, phosphor bronze and Tobin bronze since to do so will result in a poor instead of an improved machine finish.

bits for machining sprayed metal is shown in Fig. 15. Speeds and feeds for this operation are given in Table 2.

Cemented carbide tools are often used for machining sprayed metal, and machine finishes of 5 to 10 micro-in. are readily obtained. Finer finishes or close tolerances usually require grinding, and the manufacturers of metallizing equipment have published recommendations for grinding wheels and technique.

General Effect of Use of Process on Base Materials

Metallizing has very little effect on the base material. Although the metal particles reach the surface in a molten condition, they are so finely divided and so evenly distributed that local overheating is seldom a problem. The temperature of the base material usually does not exceed 300°F. in machine element work. Dis-



A-NOSE ANGLE
B-SIDE RAKE ANGLE
C-SIDE RELIEF ANGLE
D-WORKING RELIEF ANGLE
N-NOSE RADIUS

Tool No.	A, deg.	B, deg.	C, deg.	D, deg.	N, in.
1	80	0	10	As	0.030
2	80	10	10	small	0.030
3	80	15	10	as possible	0.040

All tools ground for use in Armstrong-type holder.

Fig. 15.—Grinding Tool Bits for Machining Sprayed Metal

Table 3—Relative Bond Strengths of Different Methods of Preparation for Various Base Materials (for Steel Coatings)

Method of Preparation	Base Material: Cold Finished Steel	Alloy Steel Hardened to Approximately 52 R_c	Steels Hardened to Approximately 67 R_c	Bronze	Cast Iron	2S Aluminum
Electric bonding—fine grain	4	3	5	1	4	1
Electric bonding—medium	6	5	7	1	7	1
Electric bonding—coarse	9	8	9	1 to 5[a]	9	2
Electric bonding—24 pitch full thread	10	10	10	1 to 6[a]	10	2
Grit blast (SAE G18 steel) at 90 psi. or for base hardness exceeding 50 R_c. Aluminum oxide at 90 psi.	6	4	2	3	4	3
Groove and rotary roughening tool method	10	Not applicable	Not applicable	10	10	6
Roughening tool over 24 pitch 75% thread	10	Not applicable	Not applicable	10	10	6
Rough thread—24 pitch full depth	8[a]	1	Not applicable	6[a]	9[a]	2
Metallic spray bonding over smooth surface	8	9	9	Not applicable	10	5
Metallic spray bonding over 24 pitch thread	10	10	10	Not applicable	10	8

[a] Field experience indicates considerable variation in results depending on base material analysis and operator technique. Tests should be made.

tortion and recrystallization are not encountered.

Effects of Surface Preparation.—Preparation of the surface usually has more effect on the base metal than the spraying operation, and this is one of the reasons why several methods of preparation have been developed. Tables 3 and 4 show relative values of different bonding methods. The effects of each may be summed up as follows:

1. The *rotary roughening tool* is usually employed with a groove or thread which is rounded at the bottom, and the danger of stress concentration is less than when a rough thread is used.

2. *Rough threading* should be avoided on highly stressed parts, because of the possibility of stress concentrations.

3. *Sprayed undercoats* have less effect on the base metal than any other known method of preparation. Photomicrographs show no changes in the base metal at the depth of 0.0001 inch. Shallow undercuts, with tapered ends, result in a minimum reduction in diameter and a minimum of stress concentration when this method is used.

4. *Electric bonding* lowers the fatigue resistance of some materials, by inducing a tensile stress in the surface, and by embrittlement of the base material at the surface. This is particularly true of steels which are readily quench-hardenable. Only a very thin skin is affected, however, and the loss of strength is negligible except on very highly-stressed parts. On flat surfaces having a thin section, this method may produce some distortion.

5. *Blasting* produces a compressive stress on the surface of the work, and this stress increases with higher pressures and coarser, heavier abrasives. Under some conditions, blasting may improve the fatigue resistance of the work; on thin sections, it will result in distortion.

Effects of Coating Stresses.—All sprayed coatings tend to shrink when applied, and the extent of this contraction varies with different metals. On cylindrical shapes this shrinkage imposes only a light compressive stress on the base metal and the effect is negligible. On

Table 4—Key to Bond Factors Shown in Table 3

Factor	Approximate Shear Strength in Psi. by Test	Approximate Tension Strength in Psi. by Test
10	10,000 and over	3000 and over
9	9,000–10,000	2400-3000
8	8,000- 9,000	2000-2400
7	7,000- 8,000	1800-2000
6	6,000- 7,000	1600-1800
5	5,000- 6,000	1400-1600
4	4,000- 5,000	1200-1400
3	3,000- 4,000	1000-1200
2	2,000- 3,000	800-1000
1	Less than 2,000	Less than 800

NOTE: The bond factors given in Table 3 are determined according to the above table. If shear and tension values indicate different bond factors, the *lesser* factor is used.

flat surfaces, particularly thin sections, the contraction of the sprayed coating may cause some distortion.

Effects of Heat Due to Spraying.—The blast of air which constitutes part of the spray stream of a metallizing gun prevents excessive temperature rise on most work. In general practice, machine parts are not allowed to heat above 300°F. during the spraying operation. Small pieces may require the use of an auxiliary stream of cooling air, and it is entirely possible to apply sound coatings without raising the temperature of the base metal above 100°F., if desired.

Quality of Sprayed Deposits

Mechanical Properties.—As previously noted, the mechanical properties of sprayed metals are dissimilar to those of the base metals. Tensile strength of the various steels, sprayed under normal conditions, varies between 20,000 and 40,000 psi. Compressive strength is generally high, considering the structure; all steels are well over 100,000 psi. The specific gravity runs from 82 to 94% of that of the wire used.

All sprayed metals tend to contract when deposited. The amount of contraction has been found to vary widely with different metals, and does not conform to the normal thermal contraction for these metals. Contraction sets up stresses in the deposit, and should be taken into consideration on each job, since it may be the deciding factor in determining the method of preparation and in selecting the best metal to use for spraying. Metals having a low *shrink* should be used whenever possible, especially for heavier coatings and inside diameters.

Porosity of sprayed deposits is a disadvantage where corrosion is a factor, and for such applications the process is generally limited to coatings which are anodic to the base material. For bearing surfaces, porosity is definitely advantageous; it improves the oil retention of the surface, and provides an escape for foreign matter from actively loaded areas.

Hardness of sprayed coatings, as measured on the usual type of hardness tester, may be misleading. This is particularly true of quench-hardenable steels. The hardness of the particles which make up the coating will be much higher than the overall hardness of the coating. Microhardness tests show that the particles of a straight high-carbon steel have a hardness equivalent to Rockwell C67; regular Rockwell test of the surface will show a hardness of 38 to 40 C.

Table 5—Mechanical and Physical Properties of Sprayed Metals

Metal	Specific Gravity	Rockwell Hardness	Tensile Strength, Psi.	Ultimate Strain, %	Shrinkage, In./In.
Aluminum	2.408	H-72	19,500	0.23	....
5% Silicon-Aluminum	...	B-64	37,500	0.54	....
Aluminum bronze	...	B-92	31,000	0.62	0.0048
Tobin bronze	7.461	B-64	14,000	0.51	0.010
Copper	7.535	F-78	13,000	0.45	....
Monel	7.671	F-79	....		....
Nickel	7.551	F-88	....		....
Low-carbon steel	6.673	B-90	30,000	0.30	0.008
Medium-carbon steel	6.782	B-95	34,700	0.46	0.006
High-carbon steel	6.356	C-39	27,500	0.42	0.0014
Type 420 stainless steel	6.742	C-35	40,000	0.50	0.0018
Type 304 stainless steel	6.934	B-84	31,000	0.27	0.012
Zinc	6.363	H-46	13,000	1.43	....

Tensile strength of sprayed metal is a direct measure of the cohesion of the particles which make up the coating. As such, it may be of importance even where the coating will not be stressed in tension. Some conditions of wear tend to dislodge surface particles, and tensile strength is a measure of the ability of the coating to withstand this type of wear.

Table 5 shows the important mechanical and physical properties of a representative group of metals, sprayed under normal conditions, with modern guns of the wire type. Variations in type of equipment, and in spray technique, may show results which differ considerably.

Quality Control and Prevention of Defects

Defective metallizing may result from any one of a number of causes. All of

these causes are subject to control, and reasonable care, along with a fair understanding of the fundamentals of the process, should produce consistently good work. Improved equipment and a broader knowledge of the physical properties of sprayed metal have eliminated much of the guesswork from metallizing. Below are listed some of the more common sources of trouble.

Moisture in Air Supply.—Excessive oil or water in the air supply may cause fluctuation in the flame, accompanied by poor atomization of the metal. In extreme cases, it may be blown from the gun periodically in considerable volume, and may adversely affect the coating or the bond to the base metal.

If the air is reasonably clean, an ordinary air filter between the air source and the gun hose is used. A filter on both the inlet and outlet sides of the air regulator is frequently advantageous. If the air cannot be cleaned sufficiently by these means, an aftercooler is required.

Fluctuating Air Pressure.—Some guns, particularly those not equipped with a governor, are sensitive to air pressure fluctuation. An air regulator between the gun hose and the air source is required, and it should be capable of maintaining the air pressure within fairly close limits regardless of line pressure.

Fluctuating Gas Pressure.—The correct gas balance for spraying most metals is that which results in the greatest spraying speed. If the gas balance changes, the wire will run out too far and the coating will be very coarse. Fluctuation in gas or oxygen pressure indicates the need for overhauling or replacing the regulators.

Incorrect Gas-Oxygen Balance.—The oxygen-to-gas ratio is not so critical as might be expected with most metals. Since the melting takes place close to the base of the flame, the metal is inevitably exposed to uncombined oxygen at a high temperature. Some oxide will form, even when a reducing gas-oxygen ratio is used. Further, the thickness of the oxide film on the metal droplets does not vary greatly with minor changes in gas-oxygen balance. The operator should have no difficulty in recognizing, by its color, a flame which is badly off balance. However, for really accurate control of the flow of gases, flow meters should be used. The use of flow meters eliminates guesswork in balancing the gases, and usually results in increased spraying speeds and better work.

Some metals, such as tin, copper and particularly cadmium, are adversely affected by excessive oxygen. The gas balance is generally more critical with powder type guns than with wire type guns, because the metal has much greater surface area per unit of weight.

Incorrect Wire Feed.—Sprayed metal particles vary greatly in size. A normal deposit with a wire-type gun consists of particles approximately 0.0001 to 0.0015-in. diam. (as spheroids, in transit; they flatten on impact). If the wire feed is too slow, a large proportion of the metal particles will be extremely fine. Since the oxide film thickness is nearly the same regardless of particle size, it is readily apparent that extremely fine coatings will consist largely of oxides. Such coatings are brittle, difficult to machine and susceptible to cracking. Spraying with slow wire feed is the most common cause of this trouble.

The makers of metallizing guns usually recommend the correct rate of feed for the various wires. If this rate is exceeded, the wire tip will sputter and coarse particles or lumps will be deposited on the work. This should be avoided and the wire should be fed at a rate consistent with good atomization.

With powder-type guns, a slow rate of feed will result in excessive oxidation and low deposition efficiency. If the powder is fed too fast, a large proportion will strike the work surface in an unfused state and will not adhere.

Slow Traverse on Machine Work.—In building up shafts, rolls, etc., the gun should traverse the work at a rate which will deposit only a few thousandths at each pass. If the traverse is too slow, local overheating may result. Another effect of slow traverse is the development of a laminar structure, as a result of excessive oxide and dust trapped in the surface pores. Such coatings may not take a good finish, or may even fail in service by layer separation.

Condensate.—Under some circumstances, an invisible layer of condensate may exist on the surface to be sprayed. This may result in a poor bond, even though the surface preparation is otherwise correct. A mild preheat, either with the gun or with a torch, is recommended

as a precautionary measure. Warming up the surface to approximately 200°F. is sufficient; this also tends to pre-expand the work slightly and results in less stress in the finished coating.

On large areas, and particularly on outside work, it is usually not practical to preheat. Metallizing under such conditions should be done during periods of low humidity, if possible.

EQUIPMENT USED

The equipment required for metallizing naturally varies with the type of work. In addition to the gun, hoses and immediate accessories, the equipment listed below is in common use.

Surface Preparation Equipment

Force-Feed Blast Generators.—Large areas require the use of force-feed type blast generators. Such units come in a wide range of sizes. A typical unit of average size has a capacity of 1000 lb. of sand, and may be used with a $^{3}/_{16}$- to $^{5}/_{16}$-in. nozzle. The blasting rate will depend on nozzle size, air pressure, type of abrasive and condition of work surface. With sand, on outside work, up to 300 sq. ft. per hr. may be blasted with a medium-sized machine using a $^{5}/_{16}$-in. nozzle.

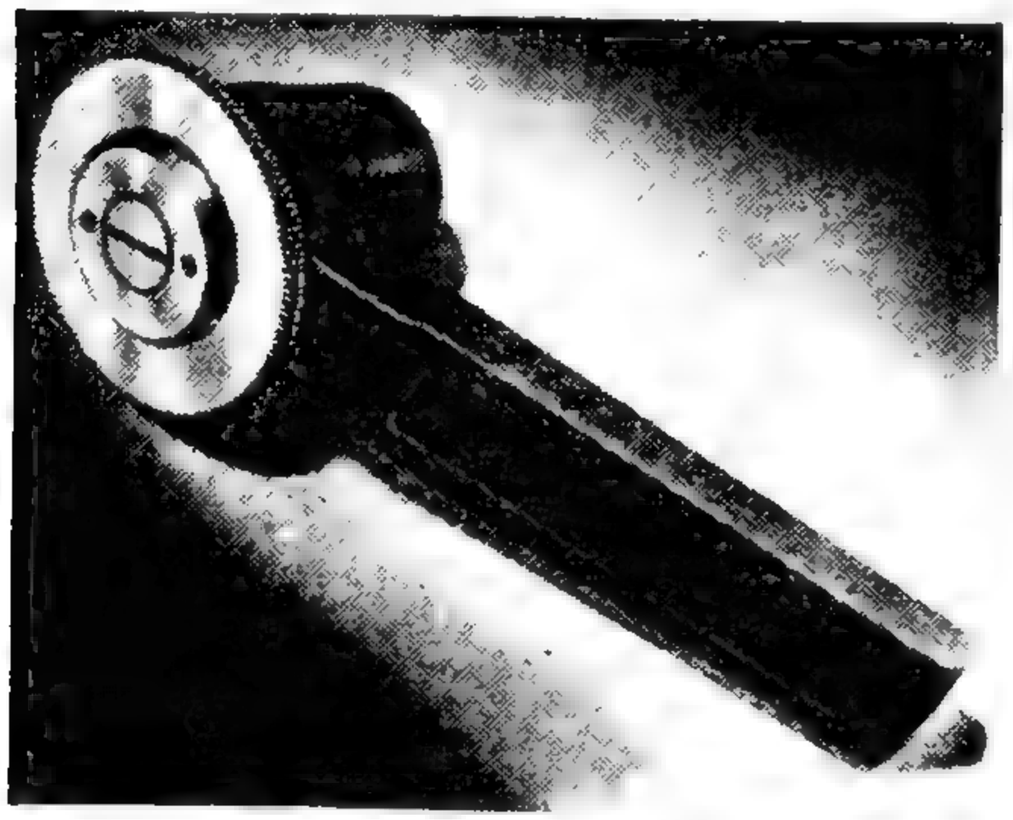


Fig. 16.—Rotary Roughening Tool

With SAE G-25 angular steel grit, in a blast room or inside a tank, 100 sq. ft. per hr. is a good average.

Suction-Feed Blast Cabinets—Suction-feed blasting uses air less efficiently than force-feed blasting, but has the advantage of being a continuous operation. A suction-feed cabinet eliminates the need of periodically reloading the abrasive hopper. For small parts which are easily handled and positioned manually, the cabinet-type blast has other advantages.

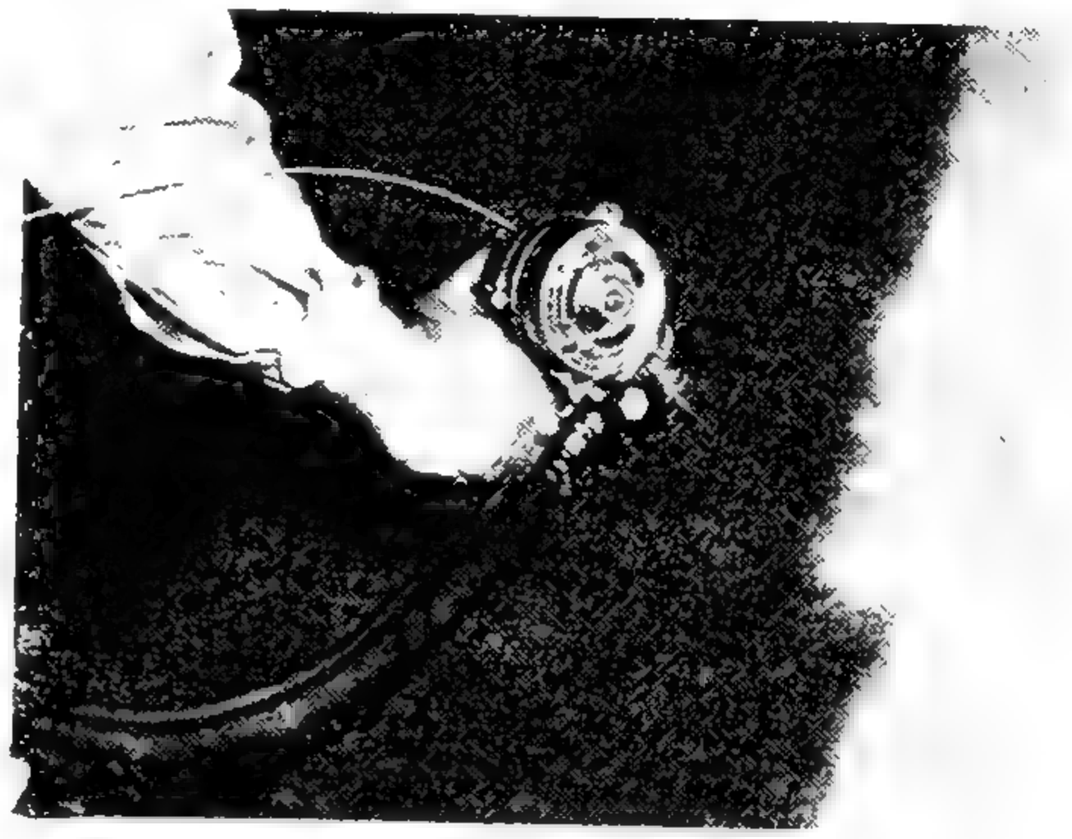


Fig. 17.—Typical Manual Metallizing Gun

The operator is not exposed to flying abrasive, and special protective garments are not required. Lost time in preparing for blasting is eliminated; this is important on small, intermittent blast operations. Used with aluminum oxide abrasive, the suction feed blast is much more efficient than when used with steel grit.

Centrifugal Blasting Machines.—Equipment of this type is usually restricted to production or semi-production applications. For such work, it offers the advantage of relatively high efficiency in terms of power used. It has the disadvantage of being somewhat less flexible than blasting equipment using air, and the initial installation cost is higher.

Electric Bonding Equipment.—Transformers suitable for electric deposition of a bonding coat may be connected to any 110–220 volt a.c. power source, either 25, 50 or 60 cycles. This method of bonding is restricted to machine parts; it is not suitable for large areas where corrosion-protective coatings are applied.

Rotary Roughening Tool.—This tool shown in Fig. 16, is used in a lathe for preparing cylindrical surfaces. It is limited to metals which are readily machinable, but provides a very strong bond on such metals.

Spraying Equipment

Wire-Type Guns.—The great majority of metallizing work is done with guns of this type. As a result, a number of

models have been developed to meet the various requirements of different classes of work.

Manually operated guns generally weigh from 3 to 6 lb., and use wire from 20 B&S (0.32 in.) to $^{1}/_{8}$ in. in size. A typical gun is shown in Fig. 17. Some handwork, especially on large areas, is done with guns using $^{3}/_{16}$-in. wire. The smaller wires are generally used where the rate of deposition must be low, or where small areas are to be covered.

For general shop work, either manual or semi-automatic guns (as on a lathe, with the gun mounted in the tool post) in the 4- to 6-lb. range are commonly used (see Fig. 18). Guns in this class usually use 11 B&S gage (0.091 in.) or $^{1}/_{8}$-in. diam. wire and spray from 4 to 12 lb. of steel per hour. Heavy-duty models using $^{3}/_{16}$-in. wire weigh 10 lb. or more and are used on large machine parts or on automatic production work (see Fig. 19). In the application of steel and other hard metals they spray 15 to 20 lb. per hour. These guns are occasionally used for manual spraying as shown in Fig. 20, in which the zinc is being deposited at a rate of 55 lb. per hour.

Modern wire guns may be used effectively with almost any combustible gas. The use of larger rod or wire has greatly increased the speed of application. Improved feeding mechanisms, with means for accurately adjusting and controlling the wire speed, have eliminated many of the former difficulties. Metallizing guns of this type consist essentially of two parts—the power unit which feeds the wire, and the gas head which controls the flow of gas, oxygen and air. The principles of operation of all wire-type guns are similar.

Although electrically-powered guns have been used to some extent, compressed air is generally employed as a source of power because of greater flexibility. The wire speed varies with the type of metal, wire size and gas used, and it is essential that the proper speed is maintained during the spraying operation. For this purpose, a high-speed air turbine, controlled by a governor or a needle valve, is used to drive a pair of knurled rolls through suitable reduction gears, and advance the wire into the flame at the correct rate.

The gas head consists of a valve or

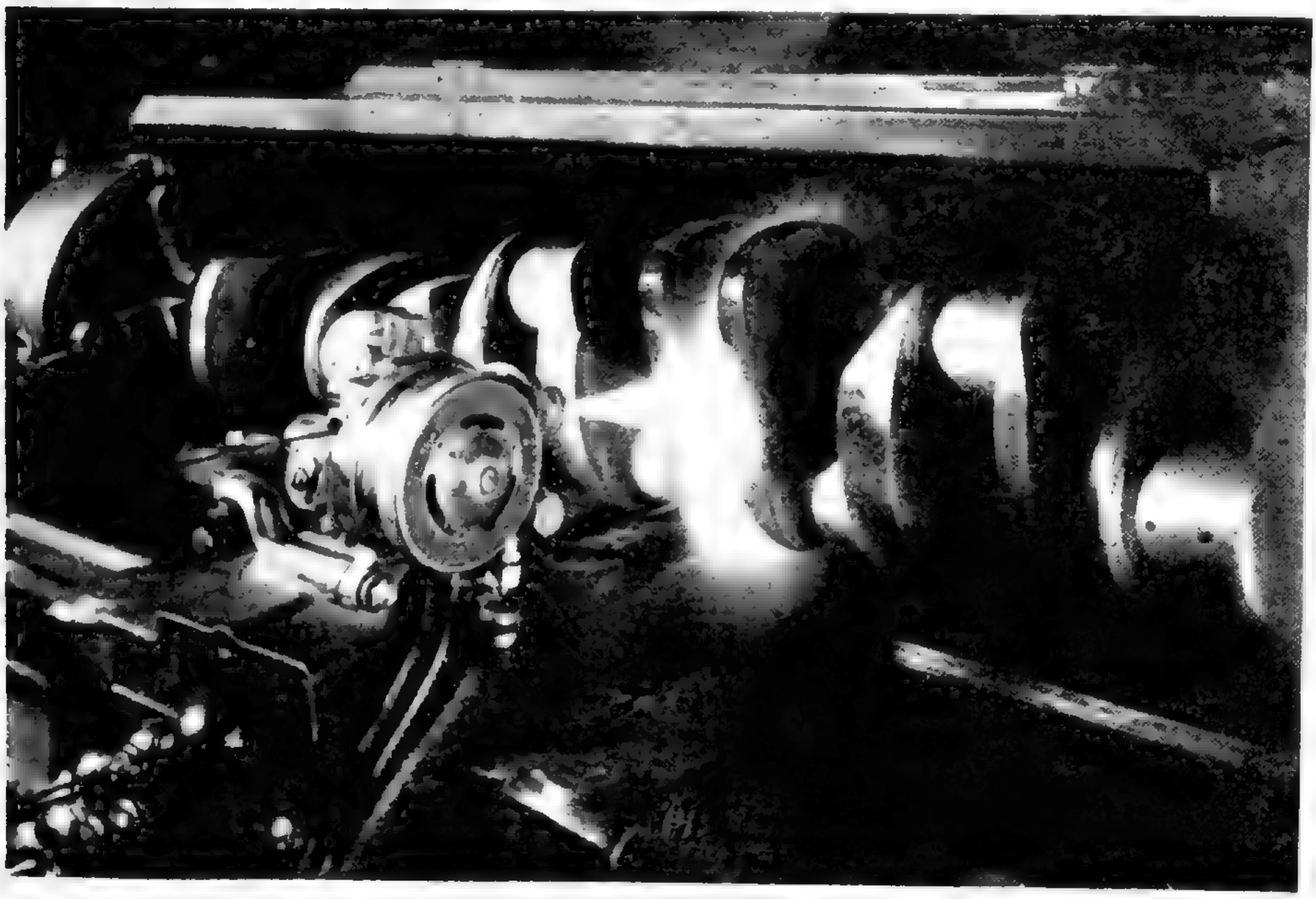


Fig. 18.—Metallizing Gun Mounted in Lathe for Building Up Crankshaft

valves to control the gas and air flow, and a wire nozzle and air cap to melt and atomize the wire. The wire is fed through a central orifice in the nozzle which is surrounded by gas jets directed against the wire at an angle. These jets are surrounded by a high velocity air stream. As the wire advances into the heating zone, it is melted by the flame and fine droplets of molten metal are picked up by the gas and air stream, and projected against the work.

If the rate of wire feed is excessive, the wire tip will extend out too far and the metal will not atomize properly. If the feed is too slow, the metal will oxidize badly and the wire may fuse in the nozzle.

Gas and oxygen pressures vary with different guns, but the volumetric ratio is generally such as to produce a neutral flame. Fairly accurate gas regulation is desirable and two-stage regulators are generally used. Although propane, hydrogen, natural gas or manufactured gas may be used, the majority of present operators use acetylene.

The compressed air supply should be reasonably free of oil and water, and a minimum pressure of 60 psi. is usually required. Modern guns use from 10 to 40 cu. ft. per min. of air, depending on size and type.

Powder-Type Guns.—Guns which use powdered metal are similar in many respects to the gas head of a wire gun, but have no power unit. Metal powder is carried in an air stream from the powder reservoir to the gun where it feeds through a central orifice in the nozzle. The powder may be ejected from the reservoir by pressure, or aspirated by a Venturi tube in the gun, or both. As the metal powder enters the flame, it is melted and propelled against the work in the same manner as with the wire-type gun. The use of powder guns is generally restricted to metals having low melting points.

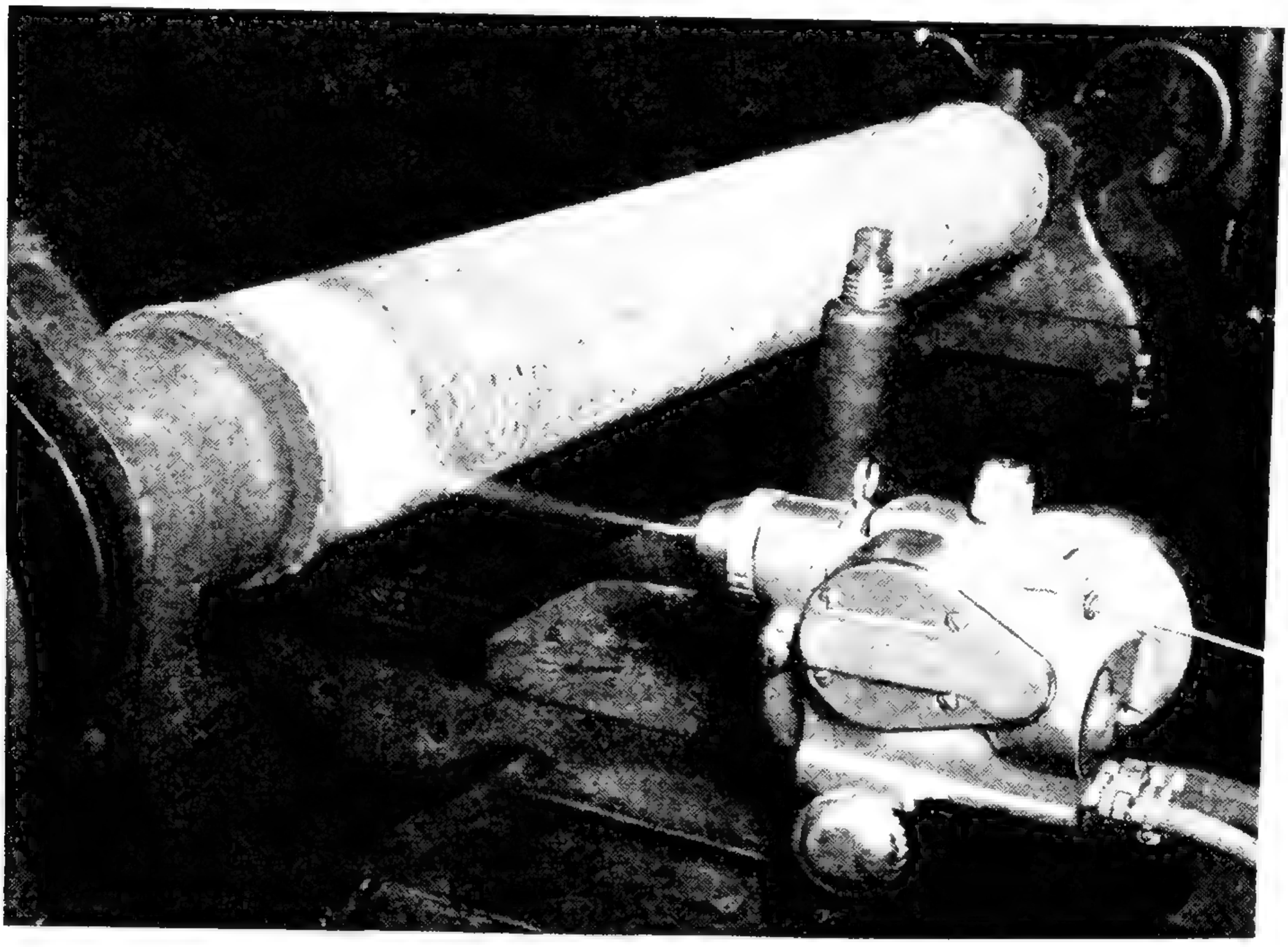


Fig. 19.—Heavy-Duty Production Type Metallizing Gun

Crucible-Type Guns.—Metals and alloys having melting points below 600°F. may be sprayed with crucible-type guns. Such guns consist essentially of a reservoir of the molten metal to be sprayed, and means

for feeding the metal into an air stream. The heat source may be either an electric-resistance element, or a gas flame directed against the reservoir. Equipment of this type is generally used for the application of solder in body and fender repair work.

Fig. 20.—Manual Operation of Heavy-Duty Metallizing Gun

Electric Arc Guns.—Some work has been done to develop metal spray guns using an electric arc as a heat source. One such gun, produced in a limited quantity in Europe, feeds two wires simultaneously and maintains an arc between the two wire tips. Because of excessive superheat, coatings sprayed with this type of equipment are usually highly oxidized and very brittle.

Gas and Oxygen Equipment

Regulators.—Although two-stage regulators are not always essential for use with metallizing equipment, they are recommended because of greater stability. Nearly all welding regulators have ample capacity for metallizing work.

Flow Meters.—The use of flow meters is strongly recommended. Not only do they provide for more accurate adjustment of the gas-oxygen ratio, but they permit immediate detection of fluctuating pressures and restrictions in hoses and guns.

Gas Manifolds.—Heavy-duty guns or multiple-gun operations may call for the use of oxygen and acetylene manifolds. Such manifolds should provide for two separate banks of cylinders, so that while operating on one bank the cylinders may be changed on the other without interruption of the work.

Gas Compressors.—Some installations operate on city gas, and require a compressor to raise the gas pressure. Such installations should be approved by the local gas company before operating.

Air Equipment

Air Compressor.—The size of the air compressor will depend entirely on the nature of the work. It is necessary to calculate the requirements, based on the number and type of guns and on blasting equipment. Some excess capacity is always advisable. For example, in a metallizing shop using three guns having a total air requirement of 85 cu. ft. per min. and a blast machine using 90 cu. ft. per min., a 50-hp. compressor, which will deliver 200 cu. ft. per min. at 100 psi. would be adequate. It is possible that all three guns and the blast machine might be operated simultaneously, and some excess air for cooling, etc., may be needed.

Aftercoolers and Filters.—Excess moisture in the air causes trouble in spraying, and even more trouble in blasting operations. A water-cooled aftercooler is almost essential, particularly on compressors larger than 10 horsepower.

Even with an aftercooler, some condensate will form in the pipe lines, and a filter is needed at the air outlet to each gun. These filters should be large enough to pass the required volume of air with a minimum drop in pressure, and should be so constructed that they may be cleaned periodically.

Exhaust Equipment

Adequate ventilation is essential for

metallizing operations. Some metals such as lead and cadmium are extremely toxic, and others such as copper, tin and zinc produce fumes and dust which are objectionable. Exhaust systems vary in type, but for manual work in a spray booth, a minimum air velocity of 200 ft. per min. through the entire front opening is required. Lathe exhaust hoods are used to pick up dust from spray operations in machine element work. Spray rooms having exhaust vents, usually at the floor level are used for spraying larger pieces.

Even the most elaborate exhaust system is inadequate for the spraying of lead and cadmium, and a force-feed type of gas mask is used. For zinc, tin, copper and other metals, a filter-type respirator may be required, depending on the nature of the work and the exhaust system.

COMMON APPLICATIONS

Sprayed metal applications fall into five broad classifications, some of which overlap. These classes may be described as mechanical, corrosion-resistant, electrical, foundry and decorative. By far the most important in this country is the mechanical class, although in England and on the Continent the process is very widely used for corrosion resistance.

Table 6—Metallizing Applications

Machine Element Salvage and Repair, Common to Many Industries:
- Restoring to size bearing surfaces on rolls, journals, motor and generator shafts, crankshafts, spindles, etc.
- Salvaging mismachined parts by adding metal where needed.
- Surfacing plug and ring gages, conveyor screws, extrusion screws and small rams, etc., by spray welding.

Foundry Applications:
- Filling in flaws in defective castings.
- Building up worn areas on metal patterns.

Corrosion Resistance Applications:
- Protecting steel structures from atmospheric corrosion.
- Protecting steel hulls and marine fittings from fresh and salt-water corrosion.
- Providing protection against mild acid and alkaline solutions.
- Protecting furnace parts, annealing pots, carburizing boxes, exhaust stacks, etc., from heat corrosion.
- Filling cavitations in turbine wheels.

Electrical Applications:
- Production of condenser plate aluminum sprayed on cloth tape.
- Production spraying of copper contacts on carbon brushes.
- Production spraying of resistance elements—grids sprayed on glass.
- Spraying of printed circuits on plastic or Bakelite bases.

Table 6 lists some of the more common applications.

Metallizing is not used extensively for decorative purposes, since the cost of finishing to a fine polish is too high to compete with plating. Some work has been done on statuary, outdoor signs, book ends and the like. Work of this sort is entirely feasible, especially where a wire-brush finish is satisfactory.

In the corrosion-resistance field, metallizing is generally limited to zinc and aluminum coatings. Although tin, lead and cadmium are used to some extent, all sprayed metal is slightly porous, and coatings which are cathodic to the base material may fail rapidly.

In the electrical field, sprayed metal has found a wide variety of uses. When used as a conductor, the resistance is 50 to 100% higher than that of the same metal in a solid form, and this must be taken into consideration in designing resistance heaters, printed circuits, etc. Figure 21 shows a radio circuit produced by spraying copper on a plastic plate.

Fig 21.—Radio Circuit Produced by Metallizing

There are several uses for the process in foundry work. Slight changes in the contour of expensive patterns or match plates may be easily accomplished. The abrasion of patterns and molds by sand-slingers has long been a problem; periodic metallizing is used to maintain proper dimensions. Salvage of expensive castings, such as motor blocks, is very common (see Fig. 22).

In the mechanical field, metallizing is used to combat nearly every type of wear. The ability of sprayed metal to absorb

and maintain a film of lubricant is a distinct advantage for this class of work. Except for severe conditions of shock or abrasion, sprayed surfaces will often outwear the original surface by a considerable margin.

The use of the process enables the design engineer to select low-cost base materials, and apply high-quality wear-resistant coatings where needed. Unique combinations such as magnesium or aluminum pulleys or rolls, surfaced with sprayed metal, present many advantages in machine design.

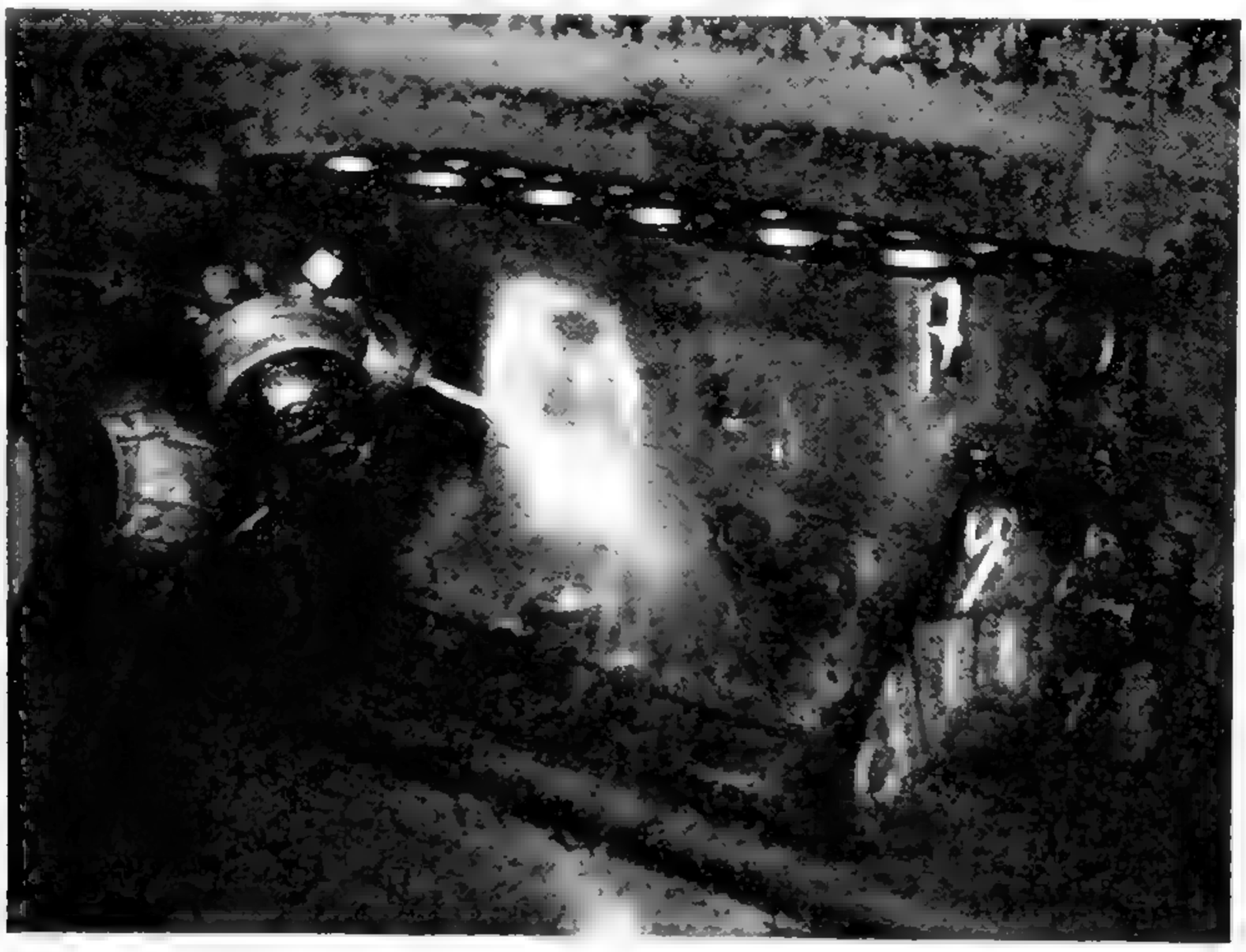


Fig. 22.—Salvaging Motor Block Casting by Metallizing

BIBLIOGRAPHY

Surfacing

1. *Steel Hard-Facing Procedure*, E. E. LeVan, The Welding Journal, April 1937.
2. *Hard Surfacing with White Alloy Cast-Iron and Copper-Nickel Alloys Containing Tin*, M. Ballay and R. Chavy, The Welding Journal Res. Suppl., October 1938.
3. *Oxy-Acetylene Application of Hard-Facing Materials to Oil Well Drilling Bits*, C. H. Shapiro, The Welding Journal, August 1939.
4. *Tungsten Carbide in Hard Surfacing Oil Well Bits*, N. J. Clark, The Welding Journal, February 1939.
5. *Surface-Hardening and Hard-Surfacing*, C. E. MacQuigg, The Welding Journal, June 1939.
6. *Hard Facing by Fusion Welding*, T. B. Jefferson, The Welding Journal, January 1940.
7. *Characteristics of the Deposits of Some Hard-Facing Welding Electrodes*, H. B. Crockett and M. L. Begeman, The Welding Journal Res. Suppl., January 1940.
8. *Hard Facing Steel Equipment*, F. L. Gray, The Welding Journal, May 1941.
9. *Hardness vs. Wear Resistance*, J. R. Spence, The Welding Journal, March 1943.
10. *Hard Facing in the War on Wear*, J. A. Gallaher, The Welding Journal, January 1944.
11. *Hard Facing*, J. R. Spence, The Welding Journal, April 1944.
12. *Metallic Arc Welding Electrodes, Part II, Hard Surfacing Electrodes*, Harold Lawrence, The Welding Journal, November 1944.
13. *Highlights of Hard-Facing Procedure*, R. L. Lerch, The Welding Journal, February 1945.
14. *Modern Hard-Facing Methods*, A. R. Lytle, The Welding Journal, December 1945.
15. *How to Select Wear Resisting Alloys for Welding*, J. A. Cunningham, The Welding Journal, October 1946.
16. *Microstructure of Hard-Facing Alloys*, H. W. Sharp, The Welding Journal, October 1946.
17. *Depositing Overlaid Surfaces by the Submerged Melt Welding Process*, L. C. Bradburn, J. M. Keir and J. E. Taylerson, The Welding Journal, April 1947.
18. *Hard Facing Materials*, H. R. Clauser, Materials and Methods, June 1947.
19. *Hard Surfacing and Fusion Welding*, H. S. Avery, American Brake Shoe Co., 1947.
20. *Hard Facing by Inert Gas Arc Welding*, K. H. Koopman, The Welding Journal, January 1949.

Metallizing

1. *How to Metal Spray*, J. G. Magrath, The Welding Journal, May 1938.
2. *Metal Spray Protection of Refinery Equipment*, D. R. Johnson and E. K. Dewey, Jr., The Welding Journal, June 1940.
3. *Procedure for Testing Metallizing Bond*, H. Ingham and K. Wilson, The Welding Journal, May 1944.
4. *Physical Properties of Sprayed Metals*, A. P. Shepard, The Welding Journal, October 1945.
5. *Metco Metallizing Handbook*, Metallizing Engineering Company, 1946.
6. *Mogul Metallizing Handbook*, Metallizing Company of America, 1946.

CHAPTER 22

BRAZING*

FUNDAMENTALS OF PROCESS

Definition and General Description

BRAZING IS ONE OF the oldest processes for joining metals by use of heat. A filler metal which melts at a temperature below the melting point of the base metal or parts to be joined is always used because the term brazing implies that the joint is made without melting the base metal.

Among the filler metals commonly used are the *spelter solders* which are composed of approximately equal parts of copper and zinc and have melting points of about 1600° F. They are supplied in granular form by crushing and screening as they are too brittle for rolling or drawing. Other brasses containing higher percentages of copper with corresponding higher melting points are used in wire or strip form, and it is possible that brazing was originally called "brassing" because of the type of filler metal commonly used. The higher temperatures required for brazing and greater strength of the bond distinguish brazing from soldering with soft solders.

There has been a phenomenal growth in the fabrication of products and equipment by joining cast or wrought metal parts. There has been a corresponding development in the welding and brazing processes; the latter involving the use of filler metals ranging from the low temperature silver brazing alloys (silver solders) melting in the range of 1100° F to 1600° F to copper base alloys or copper, requiring brazing temperatures from 1300 to 2150° F.

With increased use of brazing, different terms began to appear such as low-temperature brazing, high-temperature brazing, copper brazing, braze welding and others. Much thought has been given to defining the different metal joining processes in modern use, particularly with the purpose of indicating the general characteristics of the joint.

Welding is an old term which has been used widely in recent years as indicating a fusion or melting of the joint members along the joint, either with or without a filler metal being used. After much consideration the AMERICAN WELDING SOCIETY has adopted the following definition for brazing:

"A group of welding processes wherein coalescence is produced by heating to suitable temperatures above 800° F. and by using a nonferrous filler metal having a melting point below that of the base metals. The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction."

It is important to note carefully the limitations placed upon brazing by this definition. It does not include what is commonly referred to as braze welding. Braze welding is described in chapters discussing gas welding and copper welding.

Torch brazing, particularly if assemblies of stationary air gas burners are included, is the most widely used process. Furnace brazing and induction brazing require considerably greater capital investment but are coming into use more extensively where modern production lines are used.

A study of the grouping of the brazing processes will show that the different processes have many common factors, and in all the processes the temperature of the base metal must be lower than its melting point. It is important, therefore, to know the melting points of the base metals as well as those of the filler metals. With different filler metals having melt-

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* Prepared by a committee consisting of R. H. Leach, Handy and Harman, *Chairman;* I. T. Hook, American Brass Co.; W. C. Reed, General Electric Co.; J. J. Vreeland, Chase Brass & Copper Co.; W. M. Wilkinson, Bureau of Ships.

ing points ranging from 1100 to 1983°F., there is a wide choice for brazing different ferrous and nonferrous metals and dissimilar metals. More specific information for brazing different metals will be found in Chapters 27 to 37 inclusive.

Aluminum brazing is similar to the brazing of any other material except that aluminum brazing alloys are used. This subject is discussed more extensively in Chapter 32—Aluminum and Aluminum Alloys.

Brazing Factors

There are certain fundamental factors which have to be considered in making satisfactory joints with all brazing processes, of which the following are most important:

Design of Joint
Cleaning and Preparation
Fluxes
Jigging
Filler Metal
Heating

Design of Joint

As the definition of brazing limits the term to processes where the filler metal is distributed by capillary attraction, it follows that joints must be fitted closely. There are three types of joints: lap, butt and scarf, and the joint members may be flat, round, tubular or of irregular cross sections.

The lap or shear type of brazed joint gives the designer the opportunity for controlling the strength of the joint by varying the length of the lap. With tubular members lap joints help in jigging and supporting the members, and by lengthening the lap a higher factor of safety against leakage or failure can be obtained. Lap joints in flat strips or sheet metal allow inserts of the filler metal to be preplaced in the joint, and a light pressure during heating will assist in making a satisfactory bond.

Carefully made joints on sheet copper, brass or copper-silicon alloy, with a length of lap equal to the thickness of the base metal, when subjected to tensile tests have proved as strong as or stronger than the base metal. The joints for these tests were made under ideal conditions, with a light pressure applied during heating. In actual practice a reasonable length of lap is three times the thickness of the metal being joined. However, the stresses to which the joint may be subjected should be analyzed and in many cases a greater lap will be justified.

Clearance between the joint members is important, and experience has shown that 0.001 to 0.003 in. gives the greatest strength with silver brazing alloys. When flat sheets are being joined, a light pressure can be applied to regulate the final clearance, and a sheet of filler metal from 0.003 to 0.010 in. thick will insure a good bond.

When tubular members are joined, it is not possible to apply pressure, and the designer has to consider the coefficient of thermal expansion of the metals and method of heating. A clearance of a few thousandths will give the best results if the base metal parts have similar thermal properties and can be heated with a reasonable degree of uniformity. If the outer member is heated first, however, the expansion may make the clearance too large for best results. In that case a tight fit originally would be better.

On the other hand, if the inner member is heated first, it may expand so much that the pressure against the outer member blocks the flow of the filler metal unless sufficient added clearance has been provided. When the coefficient of expansion of one joint member varies considerably from the other's the allowed clearances need even more careful attention. For example, if the metal with the higher coefficient of expansion is the outer member, then the initial clearance might even justify a drive fit with possibly a few thousandths interference. Conversely, if the inner member has the larger coefficient of expansion then a greater clearance than normal should be provided.

Diameters of parts to be joined also have to be considered, the larger the diameter the greater the allowable clearance.

The usual tolerances allowed in machining tubular parts cause some variation in the fits when pressing tubular parts together. When steel parts are to be brazed with copper, the designer should provide for tight metal-to-metal fits if possible. Experience has shown that copper will penetrate a joint having a heavy press fit, but a light press fit will keep the parts in proper alignment for handling, and it will take less time for the copper to penetrate through the joint. A maximum press fit of 0.001 in. per inch of diameter has been recommended for

copper brazing steel parts with a maximum gap of 0.0005 inch. A uniform sleeve fit with tight metal-to-metal contact will give the best results.

Butt joints can be made that will have high strength if care is taken in fitting the joint and a clearance of 0.001 to 0.003 in. is maintained at the finished braze. Butt joints are used where the double thickness of the lap or shear joint would be objectionable. The edges or joint faces must be cut and fitted square and straight in order that uniform, close spacing can be maintained for the proper flowing of the filler metal by capillary attraction.

Scarf joints are used where it is desirable to increase the area of the bond but only the single thickness of the base metal would be suitable. Scarf joints can be made on round or flat rod, wire, sheet or tubular members. A common rule is to make the area of a scarf joint from two to three times that of the right angle area of the joint member. If the angle of the scarf joint is 30 deg., measured from the axis of the rod, wire or sheet to be joined, then the area will be two times, and if the angle is 19 1/2 deg., the area will be three times the right angle area. When tested in tension, a scarf joint will not have more strength than a butt joint in proportion to the increased joint area because the joint is partly in shear. It does have the advantage of distributing certain types of stresses over this large area where combined tension and bending stresses are involved.

Figure 1 illustrates some common designs for brazed joints and the following comments are offered as a guide to designers.

Figure 1*A* is a typical V groove that is used when making butt joints with copper base alloys or welding rods. It is a poor design for brazing because the clearance between the joint members is too great for capillary attraction to be effective. It is a proper joint for gas welding using copper base or bronze welding rods which do not depend on capillary attraction for distributing the filler metal.

Figure 1*B* shows the correct method of making a butt joint with brazing alloys. The edges should be square and straight.

The lap joint shown in Fig. 1*C* is very satisfactory. This type of joint allows the use of preplaced inserts of the brazing alloy although feeding may be done from the outside after the joint has been brought to the proper temperature. When inserts are used, the members can be clamped together and pressure exerted by the clamps will assist in making a good bond.

The scarf joint shown in Fig. 1*D* also allows the use of preplaced inserts of the brazing alloy and this method is used in joining band saws and for those joints where the double thickness of the lap joint is undesirable and greater bonding area than can be obtained with a butt joint is necessary. Copper rods which are to be drawn into fine wire are joined in this manner.

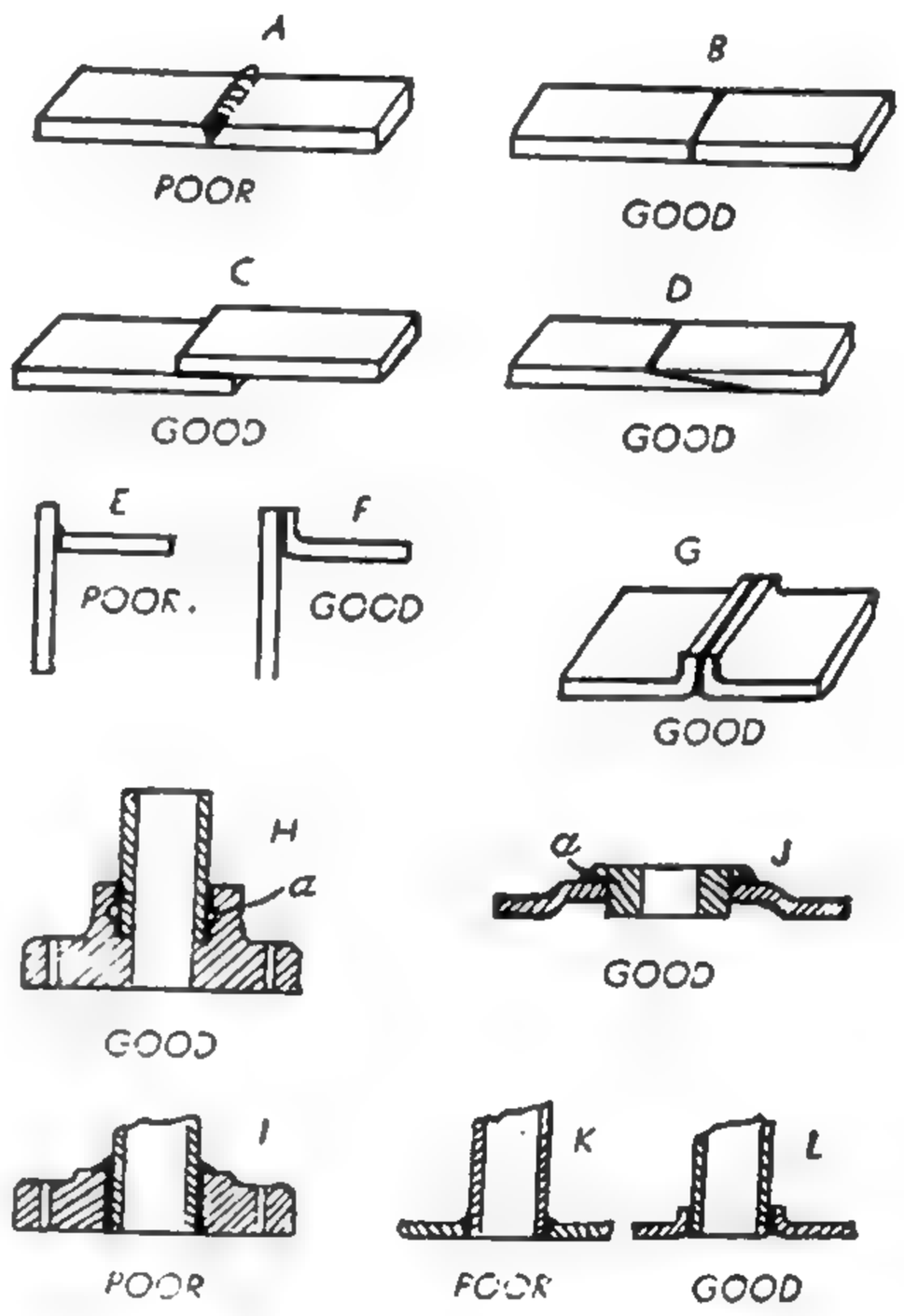

Fig. 1.—Common Designs for Brazed Joints

The tee joint shown in Fig. 1*E* is not good because the joint only has a bonding area proportional to the thickness of the metal. Heavy fillets on each side will increase the strength but they are wasteful of the alloy compared with the added strength obtained and are not recommended. It can be used, however, if for any reason it is not considered advisable to provide a flange on one of the members as shown in Fig. 1*F*.

The joints shown in Figs. 1*F* and *G* have the advantages common to all lap or shear joints and are recommended.

The joint shown in Fig. 1*H* is preferred to the one shown in Fig. 1*I* for several

reasons. The lengthened hub on the flange makes heating easier and more effective because only a small portion of the fitting has to be heated and the depth of the shear can be controlled. The use of a preplaced insert in the groove shown in the fitting at *a* regulates the amount of brazing alloy used, and a proprietary method of making joints of this design has been adopted by several large manufacturers of fittings. The brazing alloy can also be fed from the outside.

Fig. 1*J* shows a method of attaching spuds to tanks or any similar application. By preplacing a washer of the brazing alloy at *a* the members can be clamped together during heating.

Fig. 1*L* shows another application of the lap or shear type that is much superior to the joint shown in Fig. 1*K*.

When a lock seam joint is made, a thin insert of the brazing alloy can be preplaced between the members before the seam is locked. This method provides a very strong leak-tight joint.

Modifications of these designs can be made, but in all cases it is important to provide clearances that do not exceed a few thousandths of an inch. In pipe joints, particularly in the larger diameters, clearances of 0.008 to 0.010 in. may be necessary because of the difficulty of maintaining pipe diameters to closer tolerances, but where better tolerances can be maintained a clearance of 0.002 to 0.003 in. is preferable.

Drive fits or interference fits in tubular members should be considered only when the method of heating and control of the thermal expansion will assure proper spacing for the filler metal to flow at the brazing temperature. The only exception to this is when copper is used for brazing steel parts.

More specific information on joint design is given in Chapter 39.

Cleaning and Preparation

Too much emphasis cannot be placed upon the importance of having the surfaces of the base metals thoroughly clean. The surfaces should be free from grease, oxides, scale and dirt of any kind.

The two common methods of cleaning are chemical and mechanical.

Grease or oil should be removed with one of the many reliable degreasing chemicals such as trichloroethylene, carbon tetrachloride or trisodium phosphate, not by burning.

Oxide or scale should be removed by a suitable chemical dip after degreasing. It is important to rinse and dry any parts after chemical cleaning because any residual chemical may attack the surface and form an undesirable film.

When mechanical cleaning is used, it is important to remove all grease or oil with a piece of clean waste or cloth, preferably wet with a solvent such as carbon tetrachloride. Any scale or oxide can then be removed with a fine emery cloth. Sand blasting may be used but care should be taken that fine particles are not embedded in the surface, and grit blasting is preferred. Grinding with a fine wheel will remove surface scale, but any grinding dust should be removed before assembling the parts. Do not try to clean a greasy surface with emery cloth before removing the grease. Only a fine file should be used for removing scale as coarse file marks leave a poor surface for best results.

Fluxes

Fluxes are used to prevent oxidation of the filler metal and surfaces of the joint members, dissolve any oxides which may form during heating and promote the free flowing of the filler metal . They should be fluid and chemically active at the brazing temperature.

After the joint members have been fitted and properly cleaned, an even coating of flux should be brushed over the adjacent surfaces of the joint. Bare spots should be avoided because they will oxidize at low temperatures before the flux becomes fluid.

When the proper flux is used, it is a good temperature indicator for torch brazing because the joint should be heated until the flux remains fluid if the torch flame is removed for an instant.

Chemical Composition.—Common borax and mixtures of borax and boric acid have been used for many years as fluxes for brazing. Borax is fluid at 1400° F. and begins to thicken at temperatures below this point. The addition of boric acid to borax makes a more viscous flux; also boric acid is not as active as borax in dissolving oxides of metals. Boric acid is useful in protecting metal surfaces from oxidation because when heated it spreads

over the surface without bubbling like borax. The bubbling of borax when heated is caused by driving off the water of crystallization, and this can be avoided by using fused borax. Water must not be used to make a paste of fused borax as it will cake rapidly, but alcohol is suitable.

With development and extensive use of silver brazing alloys melting between 1175 to 1300° F., it became necessary to develop a flux which would be fluid and active at these temperatures. Borax can be used down to 1325° F. if extreme care is taken, but there is some chance of flux inclusions which will prevent tight joints and the activity of borax for dissolving oxides is much reduced at these lower temperatures, Moreover, these silver brazing alloys are used on stainless steel and the flux has to be active in dissolving chromic oxide. Fluxes containing fluorides and alkali salts, preferably potassium, have been developed which are fluid and active at 1100° F. They are used extensively with silver brazing alloys and are excellent for stainless steels.

Special fluxes are needed when brazing high aluminum bronzes or those bronzes to steel. The addition of one or more chlorides of sodium, potassium, zinc or lithium to the fluoride type of flux will produce such a satisfactory flux.

Form and Method of Using.—Flux is available in the following forms:

(*a*) Powder
(*b*) Paste or solution
(*c*) Vapor gas
(*d*) Coating on welding rod

Dry flux can be sprinkled along the joint, but, if a torch is used for heating, it is advisable to warm the joint before applying the flux and this preliminary heating should be enough so that the flux will adhere and not be blown away by the torch flame. When filings of powdered or granulated brazing alloy are used, the flux can be mixed with them before applying along the joint.

A thin paste is a very satisfactory form because the flux can be brushed over the surface and an even coating applied. In brushing the flux, care should be taken to go back and forth over the surface to make sure that there are no bare spots.

When using borax as a flux a hot saturated solution brushed along the joint will leave a heavy coating of flux because of the comparatively large amount of borax which can be dissolved in boiling water. Better results are obtained if this hot saturated solution is brushed on the joint than when the pieces are dipped into the solution. Experience has shown that the application of an even coating of flux on all of the surfaces to be joined is very important, and even clean pieces of metal will usually show bare spots if they are merely dipped into the solution. The filler metal should also be protected with a coating of flux.

Vapor or gas flux is usually applied to the base metal and filler metal through the medium of the oxy-acetylene flame. The acetylene or other fuel gas used is passed through a flux solution and picks up a small quantity that is burned in the flame, thus being deposited wherever the torch is directed. It should never be introduced through the oxygen hose. A fluxing constituent soluble in alcohol or methyl borate is sometimes used.

Flux-coated, high zinc bronze welding rods are commercially available and are convenient to use. However, it is desirable to flux the base metal with powdered or liquid flux as well because the surfaces may become oxidized in the heating stage. If there is considerable depth to the oxidation, the melted bronze from the flux-coated rod will flow onto some part of this area before the flux from the coating has had an opportunity to dissolve the oxides and a poor bond will result. The flux coating does, however, protect the filler metal and eliminates dipping the hot rod into flux.

Prepared fluxes are commercially available in the form of powder, paste and solution. One should keep in mind that one of the advantages of brazing alloys is their low melting points and when using them a flux should be selected that is fluid and active at the melting point of the alloy. This is particularly important in making gas-tight joints where flux inclusions might cause leakage.

Fluidity alone, however, is not sufficient, and the flux must be chemically active at the brazing temperature in order to insure that all oxide films are removed.

Jigging

Suitable clamps and supports should be provided to hold the parts securely in position during heating. The design and size of the clamps or supports will de-

pend upon the size and shape of the parts and the type of joint.

When thin inserts of brazing alloys are used, pressure is needed to insure that surfaces of the parts are brought together when the alloy is liquid.

The design of the jig or support will also depend upon the method of heating. When the whole assembly is to be placed in a furnace, consideration must be taken of the fact that the clamps and supports will be heated to the brazing temperature and will expand accordingly. Contraction and expansion with the accompanying distortion and warping must be controlled.

Spot welding at points along the joint is a satisfactory method of holding thin sheets and small stamped parts together. Consideration must be given, however, to the fact that these welds will interfere with the capillary action in the flowing of the brazing alloy if the weld completely closes the cross section of the joint and the brazing alloy must be applied on both sides of the welds.

If the heating is done by a torch, care must be taken to support the parts so that the operator can apply the flame easily to all parts of the joints; otherwise the parts of the joints which come in direct contact with the flame may be overheated.

It is also important that the parts are held firmly in place until the brazing alloy is set. The assembled parts should not be moved in any way that would throw any strain on the joint until the brazing alloy has solidified completely.

Filler Metal

As brazing processes are used at a wide range in temperatures for joining metals and alloys, there are a number of different filler metals available.

These filler metals are used in the form of wire, sheet, filings and ground or crushed grains. Most of these brazing alloys are malleable and ductile which allows them to be drawn into thin wire or rolled into sheet of the most economical size for convenient use. Special forms such as rings and washers are preplaced in joints.

The compositions include pure copper which is used on steel, copper-zinc alloys with small additions of other metals, and the silver brazing alloys which contain silver with varying percentages of copper, zinc, cadmium, tin, nickel and manganese.

The two important factors in selecting a filler metal are: it must be molten and free flowing at a temperature below the melting point of the members being joined; and, second, it must form a strong bond with those members. Alloys containing phosphorus, for example, should not be used with steel because of the formation of a brittle phosphide of iron. Similarly, excessive amounts of tin or zinc may be harmful. More complete information on filler metals is given in Chapter 38.

EQUIPMENT USED

Torch Brazing

Heating and Equipment.—Four different types of torches are commonly used for brazing depending on the gas mixtures: air-gas, air-acetylene, oxy-acetylene and oxy-other fuel gas.

Air-gas torches give the least heat and when used on heavy parts there is a tendency to use an oxidizing flame in order to hasten the heating. The air-acetylene torch uses acetylene under pressure with air at atmospheric pressure, and suitable torches are available for use with brazing alloys. Both air-gas and air-acetylene torches can often be used to advantage on small parts and thin sections. Torches using oxygen with city gas, natural gas or any of the bottled gases such as butane or propane give a much hotter flame and when properly designed give excellent results with brazing alloys. They should be of sufficient size to allow the use of a neutral or a slightly reducing flame.

Oxy-acetylene torches give a wide range of heat control and high temperatures are possible with a reducing flame. These torches have been developed to a high degree of perfection and, properly used, offer the most flexible and quickest method of heating. Their use is so universal that full information and instructions are readily available.

Specially designed torches having multiple tips can be used to advantage to increase the rate of heat input. Care should be taken, however, to provide sufficient tips to prevent localized overheating in spots before the entire joint is at proper temperature.

When the brazing alloy is to be fed from the outside, the joint should be

heated with the torch to a temperature above the melting point of the brazing alloy before the alloy is fed into the joint. In order to obtain full advantage of the low melting temperatures of brazing alloys, it is of course most desirable not to heat the joint beyond the temperature required for the free flowing and bonding of the brazing alloy. If it is overheated, a great deal of the benefit of the low temperatures at which these alloys melt will be lost. The appearance of the flux and color of the parts are important guides in determining the proper heating of the joint. However, varying light conditions may create some difficulties.

Another way to obtain some guidance as to the temperature is by touching the brazing alloy wire or strip to the joint as heating progresses. As soon as the temperature is high enough so that the alloy melts, the wire or strip is brought under the torch flame momentarily. This technique is suggested in order that an attempt to make the joint itself a soldering iron will not cause overheating. It is most important that the common expression *let the heat in the joint flow the brazing alloy* is not misinterpreted. At the same time the joint should be at a temperature above the melting point of the brazing alloy, and this procedure would be somewhat equivalent to feeding molten metal into the joint. Of course, it is not desirable to play the torch flame for any considerable period of time on the brazing alloy.

The preheating required will depend upon the size and heat conductivity of the metals and type of joint, but there should be sufficient heat in the joint for the brazing alloy to flow freely or it will *ball up* and poor joints will occur. Poor work will often result when the brazing alloy is made to flow by applying more heat. The balling up tends to pile the brazing alloy above the film of protective flux, and added heat only tends to oxidize the exposed brazing alloy. Furthermore, the higher temperature may cause rapid diffusion of the brazing alloy into the joint members where the alloy has bonded. In the case of thin sections this may be carried to such an extent that holes are obtained in the joint.

What actually happens is that the diffusion of the alloy into the members leaves open spaces which have to be filled with more alloy. The correct way to repair a joint in which the brazing alloy has balled up is to allow it to cool sufficiently so that flux can be reapplied and then the reheating can be done carefully and the alloy properly flowed into the joint.

A modification of torch brazing consists of using several fixed burners supplied from a common manifold. Natural and manufactured gases or acetylene with air or oxygen may be used. The burners are arranged in such a manner as to heat the assembled parts uniformly as they are passed between the burners. Continuous conveyor belts may be used for timing the operation by the belt speed or the assembly may be pushed into the heating zone and removed at a fixed interval of time. It is sometimes desirable to rotate the assembly as it passes through the heating zone. The method selected for handling the assemblies will depend upon the size and shape of the parts but this modified torch heating allows for high-speed production when a large number of units are to be brazed. As a rule the brazing alloy is preplaced and all joints well protected with flux. These fixed burners or torch arrangements are comparatively inexpensive to install and if the volume of work is large the automatic handling of the parts insures uniform results and low operating costs.

Furnace Brazing

Furnace brazing is used extensively when the parts to be brazed can be assembled with the brazing metal applied near or in the joint and metal jigs provided to keep the parts in proper position during heating and cooling. It is particularly applicable to brazing a large number of units.

Equipment.—Equipment for furnace brazing consists of a furnace with heating and cooling chambers, automatic temperature control and auxiliary equipment for maintaining a reducing or protective atmosphere in the furnace. Electrically heated furnaces are excellent, but gas or oil can be used for heating.

Three types of furnaces in common use are: The box, mesh belt conveyor and roller hearth conveyor. General characteristics of the three types are as follows:

A box-type furnace usually is designed with a heating and cooling chamber with a sliding door between the two chambers and doors at either one or both of the

outer ends. The work is assembled on trays and moved through in batches. It is a simple and relatively inexpensive type of furnace and can be used for a wide variety of assemblies. Small box-type furnaces do not require any mechanism for moving the trays but larger furnaces are equipped with chain drives for moving the trays from one chamber to another and automatic devices for raising and lowering the doors which divide the chambers.

Mesh belt-conveyor furnaces have heating and cooling chambers through which a mesh belt conveyor made of one of the heat-resistant alloys continually passes at a speed regulated by a variable driving mechanism. Assemblies may be placed directly on the belt which is supported by proper heat-resisting alloy rails or hearth plates. This type is suited particularly to small, light work in large quantities. The adjustable speed of the belt controls heating to the proper temperature for good brazing.

Roller hearth furnaces are more expensive and differ only in type of conveyor or carriers. As the name signifies, the hearths of these furnaces consist of a series of driven rolls which are closely spaced and extend crosswise through the furnace walls to bearings outside. Sprockets are attached to each roll and they are driven by endless chains. The assemblies to be brazed are supported on cast-alloy rails or trays which are placed on the roll table. Sometimes the assemblies are placed directly on the roll table. Speed is regulated by chain speed, and furnaces of this type can be designed for brazing light or heavy assemblies. This type is used in large-scale production work. The maintenance costs are reasonably low, and automatic charging and discharging mechanisms can often be used to reduce operating costs.

Furnace Atmosphere.—Hydrogen or dissociated ammonia which is 75% hydrogen and 25% nitrogen make excellent atmospheres. However, a great deal of furnace brazing is done in atmospheres produced by the partial combustion of natural gas, coke oven gas, butane, or propane. A typical mixture would contain approximately 16% hydrogen, 11% carbon monoxide, 5% carbon dioxide, 2% methane and nitrogen. This mixture is reducing to iron and copper at copper brazing temperatures.

Atmosphere converters for partially burning hydrocarbon gases to produce suitable protective atmospheres are available as standard equipment from furnace builders. Accessories are available for treating the gases as they leave the combustion unit in order to remove moisture, sulfur or carbon dioxide, and the complete units can be designed to produce a wide variety of different atmospheres to meet any specific condition.

Controlling Factors on Making and Supporting Assemblies.—Careful attention to design of joint, cleaning and fluxing must be given, and the assemblies jigged so that as they pass through the furnace, the proper relationship of the parts will be maintained to insure that capillary attraction will be effective. The force of gravity must also be considered when providing means for holding the parts together within the furnace and directing the flow of the brazing alloy. The brazing alloy will creep horizontally or vertically in all properly fitted joints but tends to flow downward more freely and will collect in low spots if used in excessive amount.

It is extremely desirable to fit the parts together in such a way as to make them self-supporting as far as possible and thus avoid heating auxiliary fixtures. When such fixtures are required they should be made of heat-resisting wire, strip or castings. Tubular members often can be assembled so that they are largely self-supporting.

Selecting and Applying the Brazing Alloy (Filler Metal).—One of the fundamentals of furnace brazing is the necessity of preplacing the filler metal which can be in wire, foil, filings, slugs, molten spray, powder, paste and other forms.

Practically all ferrous and nonferrous metals and combinations of unlike metals can be furnace brazed by using a filler metal which melts at a temperature below the metals being joined, wets the joint surfaces and is preplaced so that it will flow by capillary attraction throughout the joint.

With silver brazing alloys which melt at temperatures below 1200° F. as a low limit and copper at 1981° F. as an upper limit there is a wide range of filler metals that can be selected for furnace brazing. The final choice of filler metal and form will depend upon the metals being joined, size and shape of the assembly, quantity

of filler metal required and cost. Wire and foil are the most widely used forms for preplacing filler metal. Rings and washers are extensively used.

One of the widest applications of furnace brazing is for joining steel assemblies for which copper is used as the filler metal. The furnace temperature required is about 2050° F. for satisfactory copper brazing, which is too high for brazing nonferrous metals. If hydrogen or dissociated ammonia is used for a furnace atmosphere and the furnace is designed to prevent the infiltration of oxygen, it is possible to make strong clean joints at this temperature without requiring flux to help the alloy flow on low-carbon sheets. At lower temperatures, such as are required for nonferrous metals, the furnace atmospheres are not as active in protecting the joint surfaces from oxidation or reducing any existing oxides, and it is more difficult to get a satisfactory bond without using a flux. However, the flux as a rule need be used only sparingly and the parts do not become oxidized or scaled to any great extent.

When low-temperature filler metals such as silver brazing alloys are used, it is desirable to operate the furnace at a temperature considerably above that required for brazing. This higher temperature shortens the time in the furnace and is applicable to small parts of uniform mass and cross section which heat evenly. If proper control of the time in the heating chamber is provided, it is possible to use furnace temperatures as high as 1800° F. although the assemblies being brazed do not reach temperatures above 1300° F.

Induction Brazing

The use of induction heating for brazing has increased greatly in recent years. In contrast to electric resistance heating, the material being heated is placed in or near the coil carrying the electric current and is therefore not a part of a closed electric circuit. (See also Chapter 20—Induction Welding.)

The heating is due to the eddy current losses from the electrical resistance of the material and the hysteresis losses, both of which are dissipated in the form of heat. Induction heating is used on both magnetic and non-magnetic metals, the latter being heated by the eddy current losses only.

Equipment.—There are three common sources of high-frequency electric current for induction brazing: motor generator, resonant spark gap and vacuum tube oscillator.

Motor generator sets with frequency ranges from 1000 to 12,000 cycles per second are manufactured in capacities from 50 to 1000 kw. Spark gap converters with frequencies from 15,000 to 60,000 cycles and 3 to 40 kw. capacity are available and special quenched spark-type converters with frequencies from 100,000 to 300,000 cycles can be obtained in low power ratings to about 30 kw.

Electronic tube converters have a frequency range from 100,000 cycles to millions of cycles and power ratings up to 100 kw. and higher per tube.

The selection of the best source of power depends upon several factors, but if the lower ratings up to 40 kw. are satisfactory, the choice will be either the spark gap or tube oscillator. When the volume of work is large, the motor generator set may show economies in operating costs.

The following basic relation exists in induction heating: The depth of heating varies inversely with the square root of the frequency. Expressed in simple terms, the lower the frequency the greater the depth of penetration of the heating effect. With lower frequencies, heavier induction coils are necessary to produce a given heating effect because of the much higher currents required. The higher frequencies of the spark gap and oscillator types of equipment facilitate the induction of heat in restricted places and parts of irregular shape.

Induction Coils.—The design of the induction coils must provide for the production of a magnetic field in the area of the joint which is to be brazed. Copper tubing, which permits the circulation of cooling water, is a common material for these coils. Single- or multiple-turn coils are used and the number is determined by the size of the magnetic field required for properly heating the joint. Field strength depends upon the current in a single turn and by use of a multiple turn coil the field is amplified proportionally to the number of turns.

The ideal condition for the strongest and tightest brazed joints would be for the surfaces of each member to reach the brazing temperature at the same time.

Assuming that the heating can be controlled and the surfaces which the brazing alloy is to join are clean and are held to proper spacing, the alloy will flow freely by capillary attraction. The coils, therefore, should be designed so that the heating will be as uniform as possible. Because of the confined character of induction heating, it is particularly important that the coils be designed and located so that the outer surfaces of joint members are not overheated before the joint is at brazing temperature.

Another condition to avoid is the heating of one joint member to the brazing temperature causing the alloy to flow before the adjacent surface of the other member has been brought to proper temperature. This will result in a poor bond and does happen frequently in brazing tubular members unless the coils are properly located.

It is possible to provide a tight fit with tubular members and design the induction coil so that the induced heat is in the outer member and the inner member is heated by conduction. This simplifies coil design, but extreme care must be taken to insure that the fit is tight enough so that the surface of the inner member is brought above the flow point of the brazing alloy.

Rigid, solid conductors are also used. They are cooled by providing water channels or tubing around the outside of the block which is usually made of heavy copper plate. Holes are drilled in the plate of correct diameter for introduction of members to be brazed. Two or more positions can be provided for simultaneously brazing a multiple number of assemblies.

Coils can also be designed for continuous heating. Single or multiple-induction coils can be arranged to create a magnetic field of suitable size to braze the assembled parts as they are conveyed through the field. Likewise, a long tube is brazed by moving it through or past a coil at a speed which allows the tube and brazing alloy to be brought up to the brazing temperature.

Induction brazing is particularly successful when the low-temperature silver alloys are used because the rapid heating inherent in the process and the low temperature to which the joint must be heated combine to produce strong joints with a minimum of annealing or oxidation of the material being joined. Another factor which makes for speed and economy is the limited or confined application of the heat to the joint area.

Induction brazing is not necessarily confined to silver brazing alloys and can be used with brass filler metal and reports have been made of successful copper brazing by induction heating, using a protective coating of borax as a flux.

Preplacement of the filler metal is standard practice in induction brazing. Careful attention to proper jigging for holding the parts together is necessary and also for maintaining them in correct position in reference to the induction coil.

Figure 2 shows a number of the common forms of coils and plates.

Resistance Brazing

Resistance brazing has been a standardized process for nearly twenty years. The equipment, methods of application, and economics have been well determined.

The tools required are relatively simple and their proper use is easily acquired by intelligent operators. The efficiency is high because the generated heat can be localized to a definite area or section with the least loss in radiation or conduction.

The principle involved is to supply heat to the work by means of hot or incandescent electrodes. Current flow through the electrodes produces the heat proportionally to the product of the square of the current and the resistance. The resistance of the work is rarely considered.

The simplest and most commonly used arrangement is where the electrodes are in contact with opposite sides of the joint to be heated. That is, the work is assembled between the electrodes and becomes a part of the circuit. Variations of this arrangement are sometimes used where a pair of electrodes is assembled against one side of the work. The current will then flow from electrode to electrode through the work, or where a single electrode is made to contact, it is heated independently of the work.

Equipment.—The essential elements consist of a means of pressing and clamping the electrodes to the work and a source of current.

The electrodes may be attached to the anvils of press-type machines as commonly used for stationary equipment or by clamps or tongs on portable equipment.

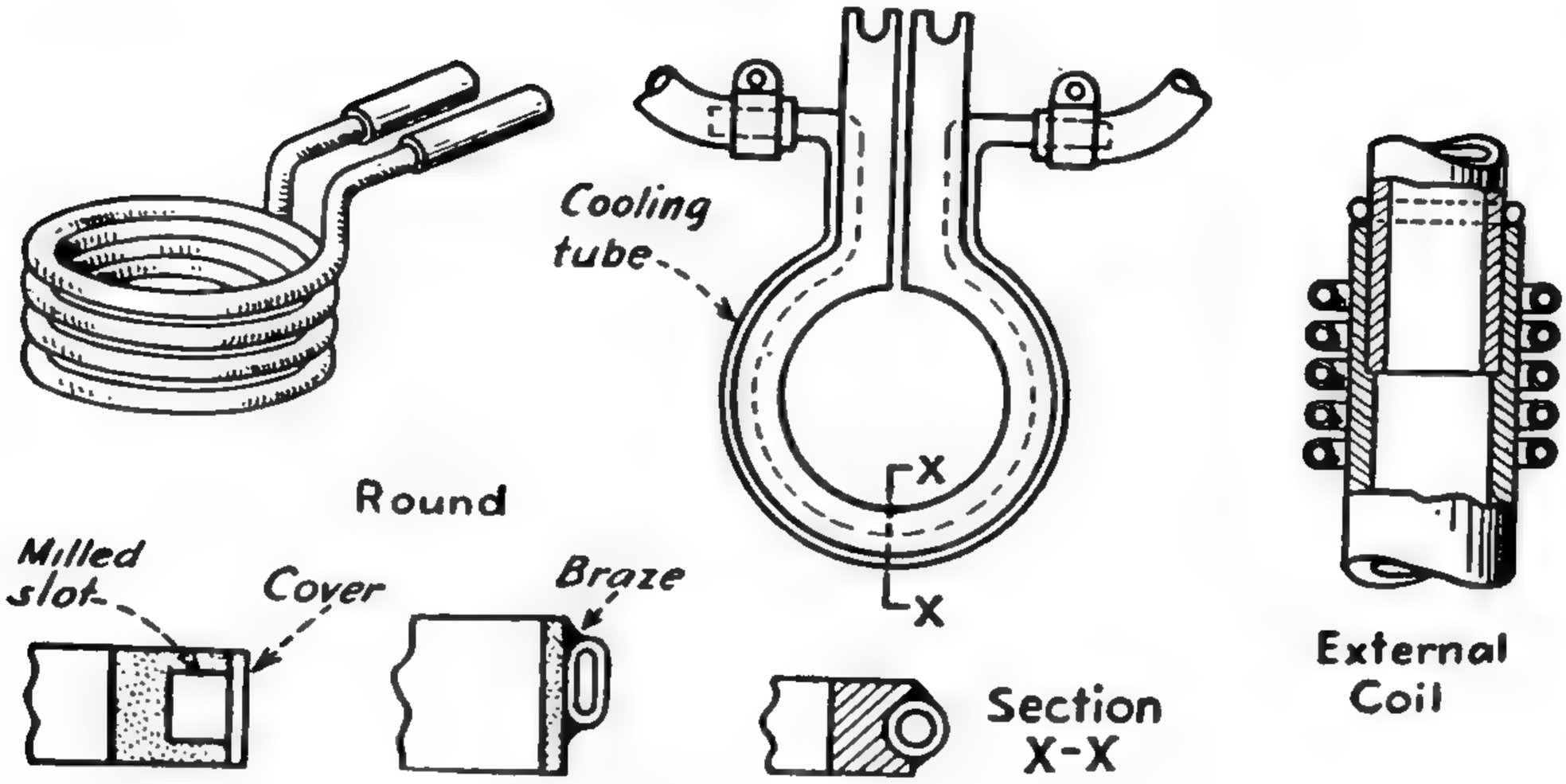

Fig. 2.—Common Forms of Induction Brazing Coils and Plates

Presses usually are designed to have water-cooled anvils with one anvil movable and means to vary the pressure applied to the work.

Sizes of presses may vary from the smallest where practically pin-point electrodes are used and where the current is measured in a few amperes, to large units using electrodes of 36 sq. in. of contacting area with current requirements up to 30,000 amp. and above in rare cases.

Tongs are clamps, which commonly consist of two arms, at the ends of which electrodes are attached, a fulcrum, and a screw, lever or spring designed to bring the electrodes together under pressure. The arm members are conductors and are electrically insulated from each other with terminals for the attachment of the current-carrying leads.

To meet the conditions imposed by the many types of joints and the positions in which they may be required to be brazed, tongs are made in a variety of sizes and forms. In general, however, they follow the principle of bringing electrodes in contact with the work under pressure.

Water-Cooled Tongs.—Tongs designed to be cooled by water are coming more and more into use. The greater initial cost of water-cooled equipment is more than offset by the several advantages.

Size and weight are reduced by at least 50%, and the reduction in cost of upkeep is 75% for large tongs. There is also a marked increase in productive capacity. The tong-conducting bars may be channeled for water passages or have water-conducting tubes formed to the bars and brazed in place.

Self-contained portable units consisting of transformer, motor, pump and radiator all mounted on a truck to which are attached the water-cooled leads, and tongs are used to great advantage. For this type of unit the transformer is usually designed to have a water-cooled secondary coil thereby making possible increased output without increase in weight or size.

Source of Current.—It is customary to use a.c. transformers. Direct current can be used for heating the electrodes but only with comparatively great expense when the heavy current requirements are considered.

Transformers are designed to match tong and press requirements. For presswork the physical dimensions are not too important as the transformer is usually made a part of the complete brazing unit. Where the current requirements are high or where the heating cycle is long the transformers should be cooled by water or air blast. On small presses, where the current requirements are usually in hundreds of amperes only, ordinary radiation is sufficient, provided the transformer has ample capacity. The following transformers have proved satisfactory by performance:

Small Press: 5 kva.—Voltage at secondary terminals = 4 to 6. Maximum contact area of electrodes = 1 sq. in.

Medium Press: 50 kva.—Voltage at secondary terminals = 5 to 7. Maximum contact area of electrodes = 10 sq. in.

Large Press: 100 kva.—Voltage at secondary terminals = 4 to 8. Maximum contacting area of electrodes = 36 sq. in.

(See Electrodes for current factors.)

Voltage changes on the smaller sized transformers are usually obtained through tapped primary windings while on the larger sizes the most efficient means is by an induction regulator. Special low voltage and corresponding high-current transformers must be used for special electrodes of material other than carbon.

Controls are always located in the primary circuit of the transformer and usually operated by foot switch. With a 5-kva. transformer it is the practice to control the secondary current directly by a foot switch of substantial design. On larger transformers the foot switch actuates a contactor which in turn controls the primary circuit.

Electrodes.—Carbon and graphite are the most commonly used electrode materials due to their high electrical resistance. For certain specific applications electrodes made from machinery steel, manganese steel, carboloy, molybdenum or tungsten are used but with voltages reduced to about one-third those used for carbon. Metal electrodes have the advantage of holding definite contour dimensions.

Experience has proved that three types of carbon electrodes meet brazing problems in general. For simplicity's sake they have been designated *soft, hard* and *extra hard.*

Soft electrodes have an electrical resistance of 0.0007 ohm-inch. They re-

duced surface burning or overheating to a minimum. They are used commonly in stationary brazing units where the high current requirements are not disadvantageous. Current densities up to 1500 amp. per sq. in. of contacting surface are commonly used. Soft electrodes are rarely used with portable equipment. The maximum thickness of electrodes used with press-type equipment is $1^1/_4$ in. giving a total resistance path of $2^1/_2$ inches.

Hard electrodes have an electrical resistane of 0.0012 ohm-inch and are used with portable equipment. Brazing temperature can be reached with approximately 30% less current than required for soft type electrodes. Current densities up to 1200 amp. per sq. in. of contacting surface are used. The maximum thickness of electrodes used with tongs is $^3/_4$ in. making a total resistance path of $1^1/_2$ inches. As the surface resistance of hard electrodes is high, care is necessary to prevent hot spots in the work.

Extra hard electrodes have an electrical resistance of 0.0018 ohm-inch. Their advantage over the soft and hard types is that brazing temperatures are obtained with approximately 50% of the current required for the soft type and 70% of the current required for the hard type. Current densities up to 800 amp. per sq. in. of contacting surface are commonly used. These electrodes are used in tongs only and only by skilled operators. This type electrode is not used in small tongs but does permit the brazing of the largest joints made by portable equipment. The maximum size of electrodes used in practice is 2 in. by 3 in. by $^3/_4$ inch. This type is much more brittle than either of the two other types.

Any type of carbon deteriorates from repeated heatings. The surfaces slough off as indicated by the carbon dust formed. This can be prevented to some degree by applying borax to the surfaces not used for contacting when the electrode is heated to a bright red heat.

Inserts of filler metal are used in most applications of resistance brazing. Lap joints are preferred and the pressure of the electrodes with both tongs and presses determines the final clearance in most cases.

When the filler metal is not preplaced, it is flowed around the joint boundaries. For example, for cables, conductor groups and laminations, the brazing alloy is introduced at the open ends where it readily fills the joint sections. In any type of joint the pressure must be retained until the alloy solidifies.

The same general rules apply for cleaning, preparation of joint and fluxing as for other processes.

Dip Brazing

Dip brazing can be performed using a chemical bath or a bath of the molten alloy.

Chemical Dip Furnaces.—A chemical dip furnace consists of a suitable metal or ceramic container in which a salt or chemical mixture can be kept in a molten state and suitable means are available for heating the bath. The work to be brazed is immersed in the bath which is maintained at the proper temperature for flowing the filler metal selected for any job.

The bath can be heated by several different methods:

1. From the outside through the retaining tank wall.
2. By electrical resistance units placed in the bath.
3. By the I^2R loss in the bath itself.

The development of satisfactory furnaces based upon the third method have to a large extent eliminated the other methods of heating salt baths for chemical dip brazing. Two types are in general use:

Type 1.—The current passes through the salt mass from the electrodes placed several inches apart but on one side of the tank. A much shorter current path results, and the work is always outside the main current flow. The amount of work does not alter the effective resistance of the bath. Heat transfer through the bath depends on thermal circulation; the fluid salt flows upward between the electrodes and spreads through the mass to the bottom. Certain baths of this type depend to some extent on the current flow from the electrodes to the tank wall.

Type 2.—The current passes through the salt mass from electrodes placed on one side of the tank but spaced not more than $1^1/_8$ in. apart. The current path is shorter than in a Type 1 furnace. The heat is distributed in the bath wholly by the *pinch effect* of the molten salts between the electrodes. This effect is very

marked and produces an active bath. This is the most efficient type of salt bath furnace so far developed. The distribution of heat through the bath is very uniform. The temperature drop of a bath during brazing is negligible.

Heating and Control Equipment.—Current is supplied to the electrodes by a heavy current transformer. The voltage at the electrodes varies according to requirements, from 8 to 15 volts. The capacity of the transformer depends on the size and shape of the bath and varies from 20 to 100 kva. or more.

The control consists of a thermocouple in the bath and adjustable control relays and contactor. Time clocks are often used. The control is set to hold the bath to a certain required temperature which depends on the material and joint design.

Salts Used.—The salts used for the bath are selected with respect to the kind of work to be heated. In selecting a salt or salt combination, a few factors have to be considered. These factors have to do with corrosion, minimum fluid temperature, maximum fluid temperature, vapor point of bath, amount of salt adhering to the work and removal of salt from work.

Chemical dip brazing has been increasingly used in recent years and is an effective medium for accurate temperature control when using brazing alloys. The correct application of this method of heating requires careful study for any particular class of work. It has been particularly successful where the brazing alloy can be preplaced in the joint so as not to be directly exposed to the salt bath. When it is impossible to place the inserts in the joint and they are placed in the form of rings, for example, on the outside, dipping may be arranged in such a way that the parts to be joined will be brought up to the brazing temperature during the immersion and the brazing alloy will then be immersed in the salt bath at practically the same moment that the parts themselves reach the proper temperature. The technique of use of the salt bath is very important in order to obtain the best results.

Molten Metal Dip Brazing

Brazing can be done by dipping the parts into a bath of molten brazing alloy. This method is largely confined to joining small parts such as wires or narrow strips of metal. The parts should be clean and well protected with flux. The size of the bath has to be such that there is no appreciable drop in temperature of the bath when the work is immersed. The ends of the wires or parts to be joined must be held firmly together when they are taken from the bath and until the alloy has thoroughly solidified.

Twin-Carbon Arc Brazing

This process is not used extensively but provides a method of extremely rapid heating.

The equipment consists of a holder constructed so that two graphite or carbon electrodes can be held at an angle and spaced to give a flaming arc. The intense heat of this arc requires careful manipulation of the flame in order to prevent overheating when used for brazing purposes.

All the factors for successful brazing with a gas torch are necessary for this method.

Flow Brazing

Flow brazing is a process in which molten filler metal is poured into the joints between the parts to be joined. It is similar in principle to the dip brazing process with a metal bath. The heating is done with a type of furnace designed for each particular job such as the brazing of bicycle frames, for example. The process is not used to any extent at the present time.

COMMON APPLICATIONS

There has been a large increase in the industrial use of brazing processes, and the selection of the best process for any particular industrial application depends upon such factors as size, number and shape of parts to be joined.

Torch brazing is used in practically all fields for either production or maintenance and for joining ferrous and nonferrous metals. It is a flexible and economical process for the production of copper tanks and steel cylinders for the storage of propane. The refrigeration and automotive industries are large users of torch brazing in making assemblies of steel, brass and copper parts. The process is also used in the manufacture of bicycles, lawn mowers, steel furniture and for the installation of brass, copper and

iron piping. Silver brazing alloys and copper phosphorous brazing alloys are used in the electrical industry for joining copper parts, and the silver alloys for joining dissimilar metals by this process.

Furnace brazing is increasing in use for mass production of relatively small assemblies in a continuous fabrication setup. Automotive parts, heat exchangers and steel propeller assemblies are being fabricated by this method. The Crosley motor is fabricated in one operation by furnace brazing the numerous parts which have been assembled into one compact unit with copper inserts at all of the joints. Silver alloys and copper phosphorous alloys are first choice of filler materials required because of the low temperatures at which they melt. However, substantial quantities of copper strip

Table 1.—Summary of Typical Brazing Applications

Brazing Process	Filler Material	Composition	Base Materials
Torch brazing	Brass brazing alloy	60% Cu, 40% Zn	Steel, copper, high copper alloys, nickel, nickel alloys, stainless steel
	Naval brass	60% Cu, 0.75% Sn, 39.25% Zn	Steel, copper, high copper alloys, nickel, nickel alloys, stainless steel
	Manganese bronze	58.5% Cu, 1.0% Sn, 1.0% Fe, 0.25% Mn, 39.25% Zn	Steel, copper, high copper alloys, nickel, nickel alloys, stainless steel
	Low fuming bronze	57.5% Cu, 0.9% Sn, 1.0% Fe, 0.03% Mn, 0.09% Si, 40.48% Zn	Steel, copper, high copper alloys, nickel, nickel alloys, stainless steel
	Nickel silver	18% Ni, 55-65% Cu, 27-17% Zn	Steel, nickel, nickel alloys
	Copper silicon	1.5% Si, 0.25% Mn, 98.25% Cu; 1.5% Si, 1.00% Zn, 97.50% Cu	Steel
	Phosphor bronze (low tin)	1.5% Sn, 0.3% P, 98.2% Cu; 2.0% Sn, 0.25% P, 97.75% Cu	Steel
	Silver alloys (no phosphorus)	5 to 80% Ag, 15 to 52% Cu Bal. Zn+Sn+Cd	Steel, copper, copper alloys, nickel, nickel alloys, stainless steel
	Silver alloys (containing phosphorus)	15% Ag, 5% P, 80% Cu	Copper, copper alloys
	Copper phosphorus	93.0% Cu, 7.0% P	Copper, copper alloys
Furnace brazing	Electrolytic copper	99.9+% Cu	Steel
	Deoxidized copper	99.9+% Cu, 0.027% P	Steel
	Brass brazing alloy	60.0% Cu, 40.0% Zn	Steel, copper, high copper alloys, nickel, nickel alloys, stainless steel
	Naval brass	60.0% Cu, 0.75% Sn, 39.25% Zn	Steel, copper, high copper alloys, nickel, nickel alloys, stainless steel
	Silver alloys (no phosphorus)	See torch brazing	Steel, copper, copper alloys, nickel, nickel alloys, stainless steel
	Silver alloys (containing P.)	See torch brazing	Copper, copper alloys
	Copper phosphorus	See torch brazing	Copper, copper alloys
Induction brazing	Nickel silver	See torch brazing	Steel, nickel, nickel alloys
	Silver alloys (no phosphorus)	See torch brazing	Steel, copper, copper alloys, nickel, nickel alloys, stainless steel
	Silver alloys (containing phosphorus)	See torch brazing	Copper, copper alloys
	Copper phosphorus	See torch brazing	Copper, copper alloys
Resistance brazing	Silver alloys (no phosphorus)	See torch brazing	Steel, copper, copper alloys, nickel, nickel alloys, stainless steel
	Silver alloys (containing P.)	See torch brazing	Copper, copper alloys
	Copper phosphorus	See torch brazing	Copper, copper alloys
Dip brazing	Brass brazing alloy	60.0% Cu, 40.0% Zn	Steel
	Silver alloys (no phosphorus)	See torch brazing	Steel, copper, copper alloys, nickel, nickel alloys, stainless steel
	Silver alloys (containing P.)	See torch brazing	Copper, copper alloys
Flow brazing	Brass brazing alloy	60.0% Cu, 40.0% Zn	Steel
Twin-carbon arc brazing	Silver alloys (no phosphorus)	See torch brazing	Steel, copper, copper alloys, nickel, nickel alloys, stainless steel
	Silver alloys (containing P.)	See torch brazing	Copper, copper alloys
	Copper phosphorus	See torch brazing	Copper, copper alloys
	Nickel Silver	See torch brazing	Steel, nickel, nickel alloys

and wire as well as brass strip and wire are being used to obtain higher strengths and for elevated temperature service.

Induction brazing is a comparatively recent development, but the process is used in many industries instead of furnace brazing because of the small amount of space required and the added advantage of having the work always visible for observation. When provision is made for automatic handling of parts, the production rate compares favorably with furnace brazing. The automotive, electrical and other industries making small assemblies find this process rapid and economical. Silver brazing alloys and copper phosphorous brazing alloys are preferred for this process because of their high fluidity at relatively low temperatures. Nickel silver may find increased use with this process because of its high flowing qualities when used with steel.

Resistance brazing is used for joining small parts usually of dissimilar metals or metals difficult to resistance weld. Manufacturers of electrical equipment use this process extensively for connecting silver contacts to other parts and joining transformer heads. The process can be used for seam brazing, as, for example, in the production of copper or steel cylinders. The low temperature filler metals in the silver alloy and copper phosphorous groups are used with this process.

The chemical bath type of dip brazing process is used by the refrigeration industry and others where the parts to be joined can be assembled and jigged so that dipping in the hot chemical bath will heat the joints properly. The process requires the preplacing of the filler metal and is primarily applicable where a large number of assemblies is to be brazed.

Dip brazing in a metal bath is limited to dipping small parts such as connecting ends of wires. Larger baths have been used occasionally where copper tubes, for example, have been assembled and the ends dipped into a metal bath to produce heat exchangers or radiators. The low temperature silver brazing alloys are most satisfactory for this process.

One of the uses of flow brazing has been for the production of bicycle frames, but the introduction of induction brazing has limited its use. There is a comparatively high loss of filler metal when larger parts are joined by dipping in a metal bath, and furnace brazing or induction brazing are being substituted for this process.

The twin-carbon arc brazing process has limited industrial use. It finds greatest use on the farm or in rural districts where electricity is available but supplies of oxygen and gas are difficult to obtain. Torch brazing will always be preferred if the equipment is available.

Table 1 gives a condensed picture of the filler metals and base metals which may be used with the different processes. However, the bronze welding rod compositions given in the table are used principally in braze welding and not in brazing processes involving capillary action. See Chapter 38 for more complete information on the composition of filler metals for capillary brazing.

BIBLIOGRAPHY

1. *Brazing with Silver Solders*, R. H. Leach, The Welding Journal, December 1934.
2. *Metals Are Brazed in Controlled-Atmosphere Electric Furnaces*, H. M. Webber, Steel, August 12 and 16, 1935.
3. *The Navy's Soldered Fittings*, M. S. Noyes, Journal American Society of Naval Engineers, February 1935.
4. *The Effect of Molten Solder on Some Stressed Materials*, G. W. Austin, Journal Institute of Metals, January 1936
5. *Corrosion Tests on 3 Silver Solders Used by the U.S. Navy in Joining a 70–30 Copper-Nickel Alloy*, M. S. Noyes, Journal American Society of Naval Engineers, January 1936.
6. *Silver Dippings vs. Soft Solders*, G. A. Bangert, The Welding Journal, October 1936.
7. *When and How Silver Solders Are Used*, R. H. Leach, The Welding Journal, October 1936
8. *A Practical Hint on the Hard Soldering with New Alloys*, A. Eyeles, Sheet Metal Industry, April 1936
9. *Low Temperature Brazing with Silver Alloys*, P. Kriegel, The Welding Engineer, August 1936.
10. *Silver Soldering by Electricity*, P. H. Ryan, Journal American Society of Naval Engineers, May 1936.
11. *New Uses of Electric Furnace Brazing Processes*, H. Webber, General Electric Review, August 1936
12. *Corrosion Resistance of Silver-Soldered Joints (A Review of the Literature)*, W. Spraragen and G. E. Claussen, The Welding Journal Res. Suppl., August 1937.
13. *Sil-Fos in Bus Jointing*, R. A. Goeller, Electrical World, November 6, 1937.
14. *Silver Alloys as Brazing Material for Studs in Tank Construction*, H. A. Folgner, Metals and Alloys, January 1937.
15. *The Use of Oxy-Acetylene Welding and Silver Soldering on Monel Metal*, F. G. Flocke and J. G. Schoener, Sheet Metal Industry, December 11, 1937.
16. *Silver Alloy Brazing of Tubes in High*

Pressure Boilers, A. W. Weir and H. M. Webber, The Welding Journal, October 1938.

17. *Silver Brazing Tubes to Tube Sheets,* L. Edelson, The Welding Journal, February 1938.

18. *Incandescent Electric Carbon Brazing,* W. Reed and L. Edelson, The Welding Journal, March 1938.

19. *Selecting Furnace Brazing Metals and Fluxes,* H. M. Webber, Iron Age, September 8, 1938.

20. *Silver Brazing Alloys in the Marine Field,* R. H. Leach and L. Edelson, Journal American Society Naval Engineers, February 1939.

21. *Furnace Brazed Joints for Parts Made of Non-Ferrous Materials,* H. H. Schmitt, Product Eng., October 1939.

22. *Dip-Brazing,* F. G. Jenkins, Metals and Alloys, October 1939.

23. *Low Temperature Brazing with Silver Alloys,* R. H. Leach, The Welding Journal, June 1940.

24. *Electric-Furnace Brazing,* E. W. Cunningham, Metals and Alloys, November 1940.

25. *Silver-Brazing Alloy and Procedures,* D. Basch, Iron Age, June 4, 1942.

26. *Silver Alloy Brazing with High-Speed Localized Gas Heating,* J. I. Butzener, Iron Age, September 23, 1943.

27. *Capillarity of Metallic Surfaces,* E. R. Parker and R. Smolnchowski, Trans. American Society for Metals, October 1944.

28. *The Application, Use and Control of Silver Solder Fluxes,* H. L. Anthony, Steel, November 1944.

29. *Controlled Atmosphere Furnace Brazing,* Steel Processing, February 1945.

30. *Silver Brazing in Aircraft Production,* J. P. Weed, Iron Age, May 3, 1945.

31. *Induction Brazing of Bomb-Burster Units,* H. R. Lebkicher, Metals and Alloys, November 1944.

32. *Silver Alloy Brazing with Induction Heating,* A. M. Setapen, Trans. Electrochem. Soc., October 1944.

33. *Electric Furnace Brazing Being Widely Extended,* H. M. Webber, November 16, 1944.

34. *Metal Cleaning Before Silver Brazing,* J. Gauthier, Iron Age, December 1945.

35. *Electric Furnace Brazing,* G. P. Tinker, J. Inst. Production Engrs., August 1945.

36. *Application of High Frequency Heating to Silver Brazing and Silver Soldering,* H. A. Folgner, Western Metals, March 1946.

37. *Design and Production Control of Silver Alloy Brazed Joints in Aircraft Structures,* H. A. Smith and P. A. Roerner, The Welding Journal, November 1946.

38. *Design Possibilities in the Silver Brazing of Cast Iron,* H. Frick, Product Engineering, October 1947.

39. *Methods for Maintaining Positions and Dimensions of Parts During Brazing,* Product Engineering, August 1947.

40. *The Inspection and Testing of Brazed Joints,* J. L. Christie and A. M. Setapen, The Welding Journal, September 1947.

CHAPTER 23

SOFT SOLDERING*

DEFINITION

SOFT SOLDERS are metals or alloys, used for joining most common metals, which melt at temperatures below the melting point of the base metal and in all cases below 800° F. The soldered joint depends for its strength on alloying with the base metal and upon mechanical bonding between the parts.

Soft solders are generally made up of tin, tin-lead or lead with or without the addition of antimony, silver, arsenic or bismuth to impart special properties. These metals or alloys behave differently than the so-called *hard solders* (silver brazing materials). The joint strength obtainable is lower and may deteriorate rapidly if exposed to high temperatures or to corrosive conditions. Continued stress reversals which may be produced by vibration or a constant load which may cause creep, also result in a very rapid drop in the joint strength.

MATERIALS AND AVAILABLE FORMS

Soft solders are obtainable commercially in the form of wire (or string), bars, powders or ingots. The wire solder is obtainable with or without flux core.

The list of soft solders given in Table 1 on the next page, includes nominal composition, types and applications.

Fluxes

The functions of a flux are to clean the joint area, prevent oxidation and lower the surface tension of the solder, thus increasing its wetting properties. Fluxes may be classified as follows:

Non-Corrosive Fluxes.—Rosin and Rosin Alcohol are truly non-corrosive fluxes. This type of flux requires that the parts be chemically or mechanically cleaned yet not polished brightly since the flux has little or no cleaning power and low wettability. A small addition of glycerin will increase the wetting properties of the flux. The addition of a small amount of lactic acid will increase the efficiency of the flux on brass parts. Some trouble is encountered in removing the brown stain which is left by the rosin. The addition of a small amount of turpentine to the flux will help to reduce this stain. This flux is used principally for electrical connections.

Mild Fluxes.—Citric acid in water is a low-cost slightly corrosive flux. If this flux is used for dip soldering, the acid should be dissolved in alcohol to reduce spatter. The addition of glycerin or sulfonated alcohol will increase the wetting action and further reduce the spatter. Levulinic acid in alcohol is widely used as a flux on terne plate and tin plate in the can industry. Mild fluxes are generally used where a limited amount of corrosion is not objectionable or where the parts can be rinsed in water after soldering.

Corrosive Fluxes.—Zinc chloride and ammonium chloride (sal ammoniac) are the best-known corrosive fluxes used in soft soldering. They may be used singly or combined in various solvents. They are quick acting and help to produce efficient joints quickly. However, if the parts are not cleaned after soldering, discoloration, corrosion, and loss of insulating properties will result. These fluxes are widely used and generally produce the most efficient joints. Zinc cut in hydrochloric (*muriatic*) acid, is most commonly used by tinners and repairmen in their work. Solidified residue of the zinc chloride and ammonium chloride salts are

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hygroscopic and each has the function of ionizing in the presence of moisture. This ionized material has the property of moving progressively along an electrical insulator and rendering it conductive on the surface. To protect the residue from moisture a coating such as petrolatum or grease is used. Removal of the protective film by washing or degreasing without removing the flux residue will allow progressive corrosion to occur.

for parts which require appreciable mechanical strength. A joint made by the combination of mechanical staking, crimping or folding, with the solder used only to seal against leakage, corrosion or to assure electrical contact is recommended where appreciable mechanical strength is required. When such a joint is used, sufficient clearance must be left for the solder to flow into the joint. This clearance will vary between 0.001 and

Table 1—Types and Applications of Soft Solders
Nominal Composition in Percent

No.	Tin	Lead	Antimony	Silver	Arsenic	Melting Range, °F. Liquidus	Solidus	Typical Uses
1	99.8	..	..	..	..	450	450	Electrical parts
2	62	38	..	..	..	361	361	Eutectic solder
3	60	40	..	..	..	370	361	Electrical and general
4	50	50	..	..	..	420	361	applications
5	40	60	..	..	..	460	361	
6	30	70	..	..	..	500	361	General purpose low
7	20	80	..	..	..	525	361	tin solders
8	15	85	..	..	..	550	361	Body solder
9	5	95	..	..	..	595	570	High-temperature solder
10	38	62	..	..	0.1	460	361	Wiping solder for lead
11	32	66	2	..	0.1	465	367	pipe and cable sheath
12	..	97.5	..	2.5	..	590	590	Silver-lead-solders for
13	..	96.5	..	3.5	..	603	590	high-temperature use
14	3	92	5	..	..	545	463	High-temperature
15	1	97.5	..	1.5	..	589	589	solders

The above alloys Nos. 2 to 9, inclusive, may or may not have antimony, silver or bismuth added to impart special properties. So-called *fuse alloys* are not included since their use as solders is very limited.

Antimony tends to increase surface tension in the solder deposit but when force is exerted to release surface tension, its flow properties are better than tin-lead solder of the same tin content.

Silver and antimony both tend to increase both the liquidus and solidus temperature. Silver tends to lessen the decrease in strength due to aging.

Bismuth added to solders tends to decrease the liquidus and solidus temperature but the solder is both hot and cold short. Dut to its brittleness, bismuth solder should not be used as a gas seal or for joints subject to vibration.

Aluminum solders are generally of tin-zinc or tin-cadmium composition, most of the analyses in use being proprietary.

Additions of glycerin or free hydrochloric acid to the corrosive fluxes may be necessary for particular jobs. The solvents commonly used in making these fluxes are water, where applicable, and alcohol, especially for dip soldering or tinning operations. Alcohol is a good solvent for cleaning the parts but is rather expensive to use since it soon becomes contaminated with the flux. Alkaline cleaners, such as sodium phosphate or soap solution, followed by thorough rinsing in clear water are the least expensive means of removing residues. The cleaning should be done immediately after soldering if corrosion is objectionable.

METHODS AND PROCEDURES

In general the joints obtained by the use of soft solders are not recommended

0.010 in. depending on the materials to be joined, the flux and the solder used. As a rule the tin-lead solders with the higher tin content perform satisfactorily with the lower clearances while the lower tin content solders, being more sluggish, require larger clearances.

The parts to be soldered should be free from all oxide, scale, oil and dirt to insure sound joints. Cleaning by mechanical abrasion or chemical means is a necessary prerequisite to a sound joint. A flux is generally used to secure good joints except in some cases on aluminum. It is possible to make satisfactory joints on aluminum using special aluminum solders simply by mechanical rubbing of the soldering iron over the joint until alloying occurs. The milder the flux the more necessary it becomes to have the parts clean. The more active fluxes com-

bine some cleaning with their fluxing action.

The material may be heated in any of several different ways. The most common method is to use a heated soldering iron (sometimes called a *copper*), melting the solder directly onto the iron and heating the parts by conductivity through the molten solder or by physical contact with the iron. The copper point of the iron may be heated by several means. The largest number of production irons are electrically heated. In isolated locations, gas or charcoal furnaces or torches may be used. A familiar method is to heat the copper point with a burner built into the iron, burning a mixture of gas and air.

One of the fastest means of heating is the flame obtained from one of several kinds of torches. When the flame is of considerably higher temperature than the protective temperature of the flux, i.e., the maximum temperature at which the flux is effective as an oxide preventive, the flame should be directed away from the joint and the parts brought up to temperature by indirect heating. When gas and air are used, flame temperatures as high as 2800° F. are reached with low fuel cost. Gas and oxygen are sometimes used, the temperatures obtained and the cost both being somewhat higher. Oxygen and acetylene are very fast but more expensive.

Dip soldering is a fast, efficient method of soldering light parts. However, with sufficient thermal capacity heavy parts also may be dip tinned. Parts which are to be dip soldered should be fastened mechanically leaving a joint clearance of 0.002 to 0.004 inch. For rapid heating the temperature of the solder bath should be at least 100° F. above the liquidus temperature but the operating temperature should not be so high as to cause oxidation of the metal to an extent that frequent skimming of expensive dross is necessary. In some cases a protective coating of flux on the pot will reduce the drossing and speed up soldering.

Induction heating is a fast, clean method of heating where the parts can be assembled with the solder and flux preplaced.

Resistance heating using low-voltage high current such as is obtained from a resistance-welding machine, may be used to heat the parts to be soldered. The use of high-resistance electrode facings such as carbon, molybdenum or tungsten will tend to give fast localized heat.

Wiped joints using solder with a wide plastic range are used for sealing on lead cable and pipe.

BIBLIOGRAPHY

1. *The Jointing of Metals, Pt. 1, Soft Solders and Soldered Joints,* S. J. Nightingale, Res. Rept., British Non-Ferrous Metals Research Association, No. C234-214, December 1939.

2. *Seams for Copper Roofing,* K. H. Beij, Bureau of Standards Journal of Research, Paper 216, 1930.

3. *Tin Solders,* S. J. Nightingale (Introduction by R. S. Hutton), British Non-Ferrous Metals Research Association, 1932.

4. *Strength of Soft Soldered Joints in Copper tubing,* A. R. Maupin and W. H. Swanger, Bureau of Standards Circulars Nos. BM-558, 1940, and BM-583, 1942.

CHAPTER 24

OXYGEN CUTTING*

FUNDAMENTALS OF PROCESS

Introduction

THE INTRODUCTION of the first cutting torch into this country about 1907 made a profound change in industrial practices having to do with the shaping of steel. Shears can be used to cut low-carbon steels in thicknesses up to about $1^1/_2$ in. only and higher carbon and alloy steels must be even thinner. Other methods of shaping heavier sections are expensive and generally require that the work be transported to the machine. The cutting torch, which is capable of cutting metal 48 in. or more in thickness provides a tool that can easily be taken to the work and can be used for cutting not only in straight lines but, by means of mechanical guiding can be used for cutting all manner of shapes to fairly accurate dimensions.

Oxygen cutting has been developed to a high degree, and the various factors which affect the quality, economy and relative success of the operation have been given serious study. As a result it is possible to evaluate fairly accurately the metallurgical, chemical and mechanical changes of the metal accompanying and attributable to the cutting.

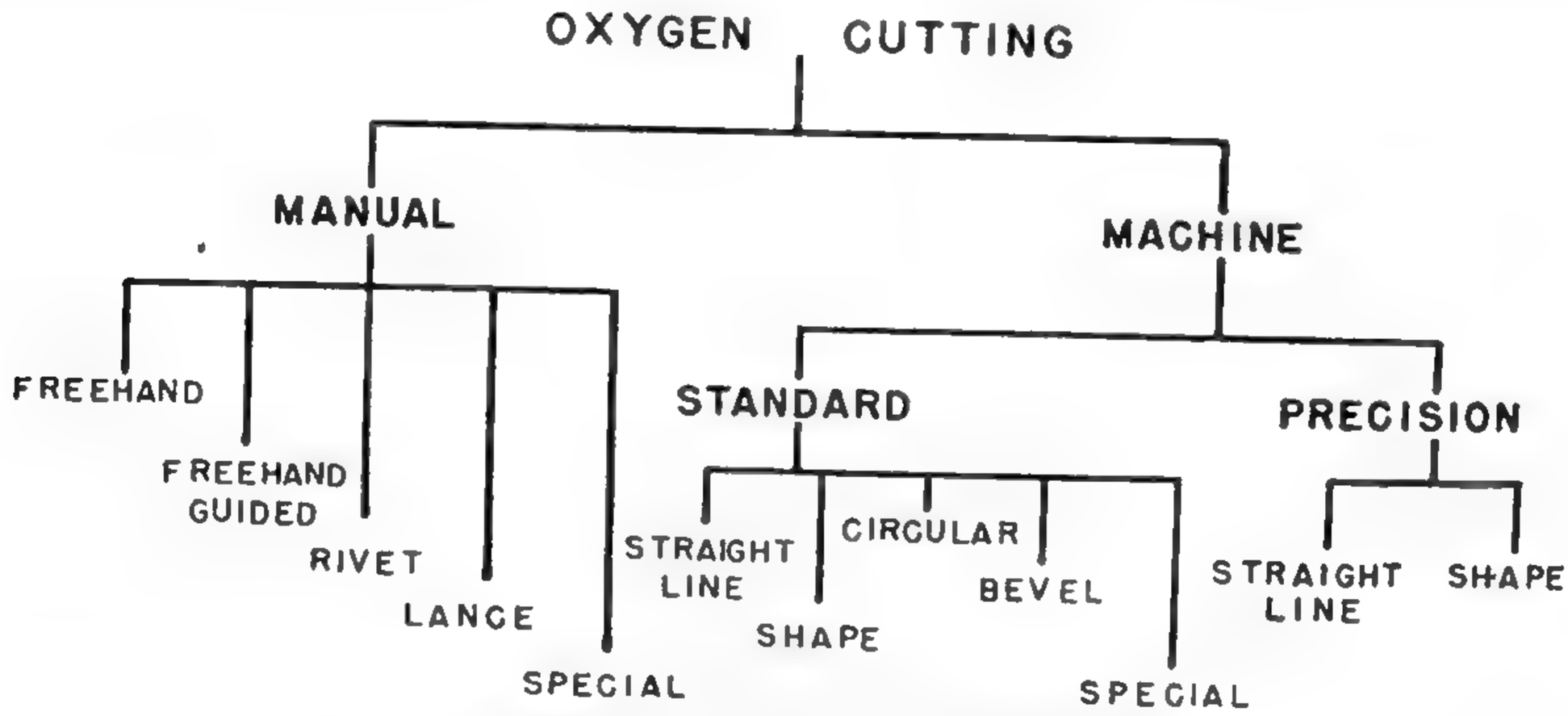

Fig. 1.—Classification of Oxygen-Cutting Processes

Definition and General Description

Classification of Cutting Processes.—Oxygen-cutting processes may be classified under two subdivisions, oxygen cutting and oxygen machining. The former includes most severing operations, and is the subject of this chapter. The latter, oxygen machining consists of various surface-shaping operations, which are treated in detail in Chapter 26A.

A further breakdown of oxygen cutting is shown visually in the chart shown in Fig. 1.

This chapter is devoted entirely to those processes shown in Fig. 1, a separate discussion being provided for each. It is interesting to note at this point, however, that all of these processes are proved and extensively used commercial proc-

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esses, none of them being in the experimental or development stages, all being used as production operations.

This same statement does not apply to the oxygen-machining processes covered in Chapter 26A.

Manual Oxygen Cutting.—Manual oxygen cutting is the process whereby the tip of a cutting torch is directed at the material to be cut and is guided by hand along the line of the cut. In manual oxygen cutting the torch is advanced and controlled by the operator's hand, so that the quality of the cut is mainly dependent upon the skill of the operator in adjusting, guiding and advancing the torch in the proper manner.

Machine Oxygen Cutting.—For many operations, it is advantageous to mechanically hold, guide and advance the torch along the work as a means of improving the quality of the cut. When practicable, mechanically guided, oxygen-cutting equipment will result in better workmanship, accuracy and economy than with manual equipment.

Fig. 2.—Typical Shapes Made With Machine Oxygen Cutting

Machine oxygen cutting in a straight line is even simpler than manual oxygen cutting. Once the machine and gas pressures have been adjusted the torch follows the line of cut automatically. It need only be advanced uniformly at proper speed, either manually operated or power driven One type of portable, motor-driven machine runs on sections of straight track, which guide the machine and the torch mounted upon it.

Shape-cutting machines are usually electric-motor driven although other sources of power are used. Some have tracing devices which are manually guided around the outline of a drawing or template of the required part. Some machines are fitted with motor-driven guide rollers, which automatically follow a template of the required shape, simultaneously controlling the movement of the torch so as to cut the same shape. One or more torches mounted on the machine duplicate the motion of the tracing device over the work, thereby cutting the shape traced. Motor-driven, magnetized rollers, which adhere to steel templates as they advance automatically around the contour, are a feature of certain machines. A yet more elaborate development in tracing devices is the electric eye tracer which, by means of a spot of light projected from the tracer head mounted on the machine follows the outline of a drawing of the piece to be cut.

Most oxygen-cutting machines may be adapted to circular cutting. With some, an adjustable-length radius rod with a center point is furnished.

Some typical shapes, for which machine oxygen cutting is adapted, are illustrated in Fig. 2.

Scrapping.—Scrapping differs from manual and machine cutting in that its object is to sever the metal without regard to the quality of the cut. The major purpose of scrapping is for cutting unwieldy steel sections into smaller pieces for easy handling during demolition work, or for salvaging waste materials so they can be returned to steel mills and foundries for re-use as raw materials in steel making.

Lance cutting by itself, or in conjunction with machine cutting, is used for scrapping operations involving very heavy thicknesses. In fact, lance cutting is not confined to the cutting of steel. It has been used successfully for the piercing or cutting of nonferrous metals and even non-metals such as concrete vaults or foundations.

Rivet cutting is yet another scrapping operation made easy and quick by use of the oxygen-cutting torch. For removing damaged sections in railroad maintenance and ship repair, the cutting torch used for rivet cutting is widely accepted.

Chemistry of Oxygen Cutting

If iron or steel is heated to a temperature of approximately 1600° F.* and comes in contact with oxygen, the iron is immediately oxidized. The phenomenon of combustion of iron in oxygen is analogous to the combustion of coal in a furnace. If the coal is heated to the kindling temperature in an atmosphere of air (air contains roughly 20% oxygen) the coal burns or oxidizes. Likewise if iron is heated to the ignition or kindling temperature in contact with oxygen it burns or oxidizes very rapidly.

The chemical equation for this reaction is as follows:

$$3Fe + 2O_2 = Fe_3O_4$$

In the process of oxygen cutting, advantage is taken of the capacity of pure oxygen to combine rapidly with iron that has been heated to the kindling temperature. Theoretically, 4.6 cu. ft. of oxygen will oxidize 1 lb. of iron to Fe_3O_4, but in practical cutting operations where proper attention is given to the variables involved, the amount of oxygen used is appreciably less. This is because not all of the iron is oxidized to Fe_3O_4. Some unoxidized or only partly oxidized metal is removed by the force of the rapidly moving oxygen stream. Analysis of the slag has shown in some instances over 30% to be iron which has not been oxidized.

The heat generated by the combustion of 1 lb. of iron to Fe_3O_4 is 2900 Btu. and the high temperature resulting from the liberation of this heat melts some of the iron adjacent to the reaction surface. This molten iron is swept out by the rapidly moving stream of oxygen and iron oxide. Most of it is oxidized before it is blown clear of the cut and thus furnishes heat for melting another layer of iron at the active cutting front. Because oxidation is not an instantaneous process, the heat developed by oxidation of the iron removed from the uppermost level of the cut is liberated for the most part at a somewhat lower level. For this reason it is necessary to make up the thermal deficiency at the uppermost level by means of preheating flames at the torch tip, which burn continuously while the torch is in motion.

Many of the impurities and alloying elements in steel, when present in small amounts, are oxidized or dissolved in the slag without interfering with progress of the cut, but this is not true of some of the alloying elements when present in appreciable amounts. While steels containing these oxidation resistant elements can be cut, the technique required is quite different from that used with the plain carbon or low-alloy steels.

Torch and Tip Operation

Essentially, the cutting of iron or steel by the oxygen cutting process merely involves the direction of a jet of pure oxygen onto an area that has been previously heated to the ignition or kindling temperature, and as the iron is oxidized, slowly and uniformly moving the jet along the line to be cut. If the cutting is to be continuous, however, it is necessary to supply heat to the steel just ahead of the oxygen stream. In the early applications of the process, the required heat, called *preheat*, was supplied by the flame of a welding torch. In fact, the cutting operation was carried out with an oxygen

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* The ignition temperature of iron or steel of 1600° F. is a figure which is time honored, but which we believe is considerably lower than that actually required before sizable steel bodies can be attacked by the oxygen stream. Laboratory tests have indicated that furnace heating of steel billets to 2200° F. is necessary before ignition with the oxygen stream can be effected.

nozzle attached to a welding torch, the heating flame of the welding torch being positioned in advance of the oxygen jet. Such an arrangement had the disadvantage that it required careful manipulation to insure that the preheating flame always preceded the cutting jet, and this was particularly difficult when the contour of the desired cut was other than a straight line.

Modern torches are equipped with separable tips commonly called *cutting tips* in which the oxygen-cutting jet is surrounded at a proper distance by several preheating flames (see Fig. 3).

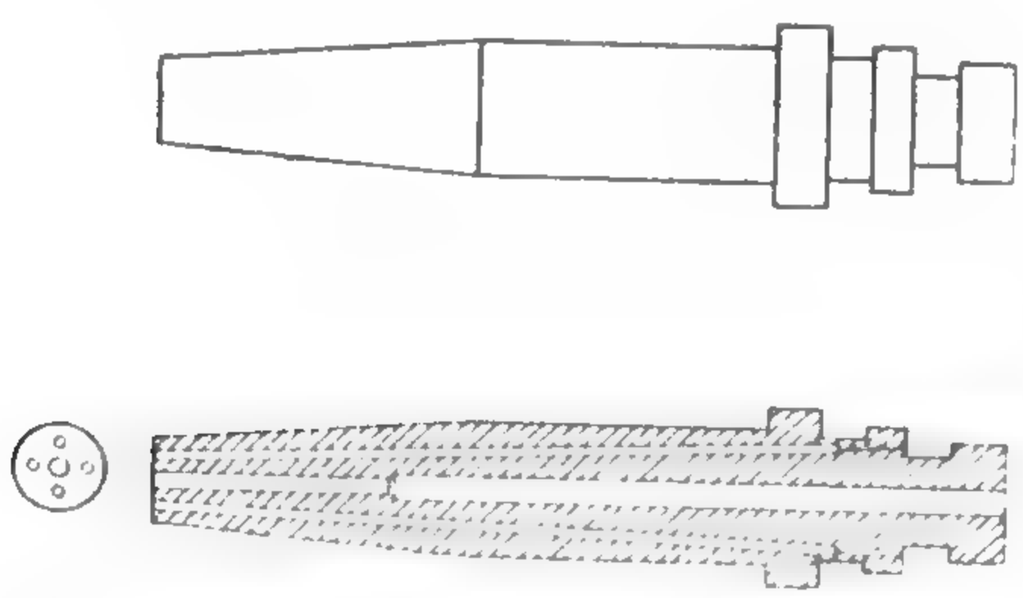

Fig. 3.—Diagrammatic Representation of Typical Cutting Tip

With this arrangement the torch may be moved in any direction without losing the effect of the preheating flames. In addition a uniform distribution of the preheating flames around the cutting-oxygen stream helps to stabilize it and insures a smoother cut surface, particularly when cutting heavy sections. Individual valves are provided for controlling the gas flow, so arranged that there is independent control of the fuel gas used for preheating, the oxygen for preheating and the oxygen used for cutting.

Basic Cutting Procedure

In all oxygen cutting, the preheating gases are first lighted either with a spark lighter or pilot light and the pressures adjusted so that the flames are stable both with or without the cutting oxygen flowing. The preheating flames are then directed toward the work at the edge of the metal where the cut is to be started. The preheating flames are allowed to play upon a small area until a bright red spot appears which indicates that the metal is at its kindling or ignition temperature. The cutting oxygen valve is then opened, and with the preheat flames still burning the torch is advanced at a steady rate along the line of the cut. When cutting is started within the work-piece, the procedure must be modified to prevent the slag from blowing back at the tip. This is achieved by holding the tip at a slight angle until a hole has been pierced.

In cutting ordinary steel, the tip should be held perpendicular to the work-piece at a uniform distance above the surface. Usually the tip is held at a distance from the material such that the ends of the inner cones of the preheating flame just clear the surface of the metal. In straight line cutting, it is usual to hold the torch in such a manner that the preheating orifices straddle the line of cut. The torch is advanced steadily at the proper speed with as little wavering as possible. If the speed of traverse is too great, the slag and oxide emerging from the bottom of the cut will trail back at an angle. When this is the case there is imminent danger of the stream suddenly failing to penetrate the steel completely. The operator, whether using manual or machine cutting equipment, must closely observe the slag emerging from the bottom of the cut or the general nature of the course pursued by the oxygen and slag stream as it traverses downward through the steel, and make adjustment of the speed of travel accordingly. If the movement is too fast, the cut may be lost completely and have to be restarted.

Fuel Gases For Oxygen Cutting

Several fuel gases are used for preheating in oxygen cutting, the selection being largely the result of economic considerations. It is essential, however, that the torches and tips used be designed primarily for the particular fuel gas to be used, if the best results are to be obtained.

The function of the preheating flames is twofold. On the one hand, in starting the cut, enough heat must be applied to the steel to raise it to the ignition temperature. On the other hand, during the actual cutting operation enough heat must be transmitted to the upper surface of the steel to maintain the thermal balance, as explained in the section on Chemistry of Oxygen Cutting, and to dislodge or melt through the thickness of any heavy rust, scale or paint.

A preheat intensity which is sufficient to raise the steel to the ignition temperature rapidly will also be sufficient for

rapid and highly economical cutting. The expression *preheating time* merely signifies the time required to heat the steel to the ignition temperature; that is, to a temperature sufficiently high that, when the oxygen cutting jet is directed onto the heated locality, oxidation will be initiated and the cutting operation will begin.

vantages for heavy cutting because of the characteristic long flame. Its disadvantage is its relatively low Btu. value per cubic foot. In underwater cutting its usefulness lies in the fact that it can be safely compressed to the pressures necessary to overcome water pressures at depths at which salvage operations are

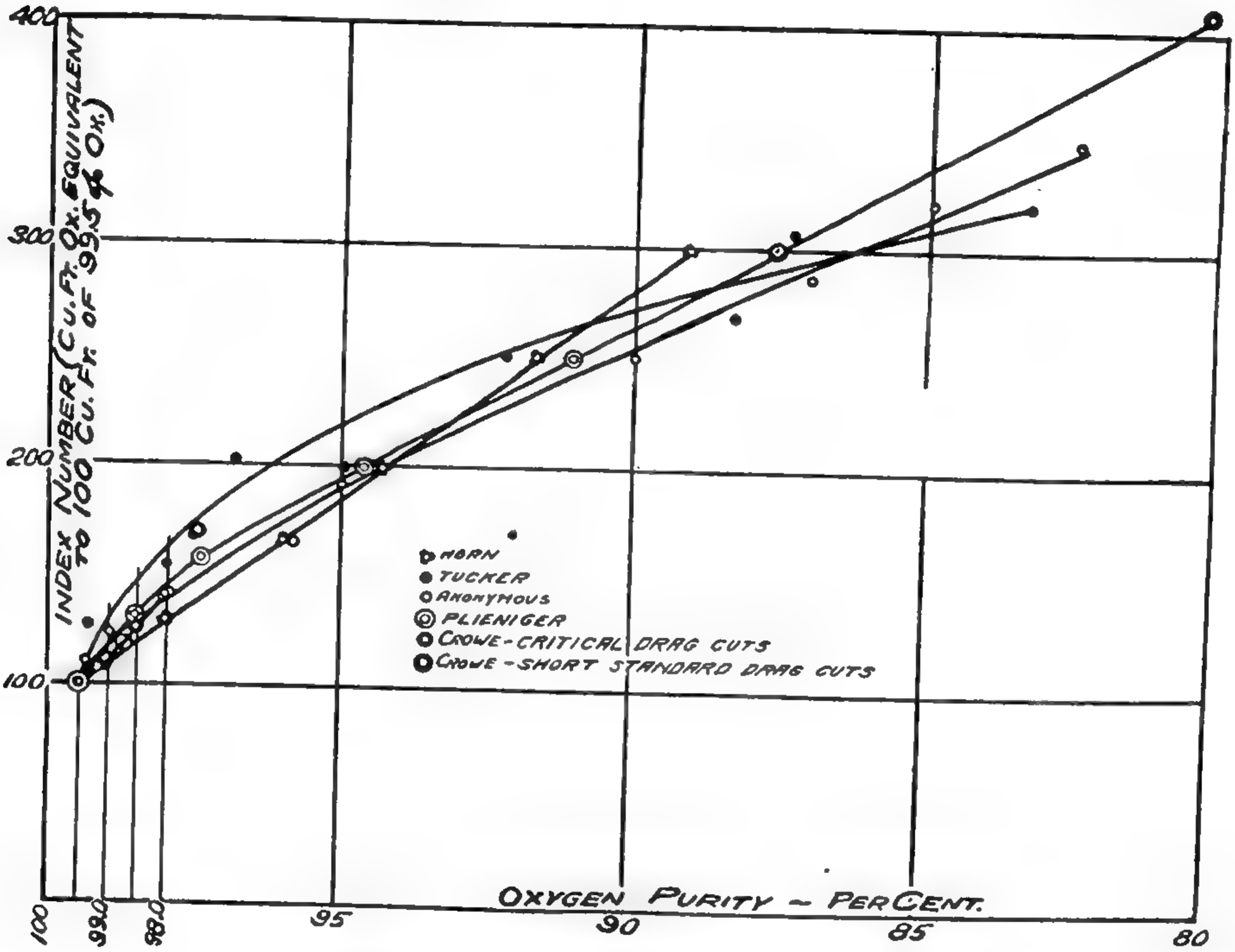

Fig. 4.—Oxygen Purity vs. Equivalent Oxygen Consumption

Listed below are the more common fuel gases used for preheating, together with some of the basic advantages of each of them. Charts listing the constants of the various fuel gases will be found in Figs. 3, 4 and 5 of Chapter 4.

Acetylene.—This gas is the most widely used fuel gas in oxygen cutting. Its chief advantages are availability, high flame temperature and widespread familiarity with its flame characteristics. The high flame temperature is particularly important when the starting time (such as for short cuts) is an appreciable fraction of the total time for cutting.

Hydrogen.—At present hydrogen is preferred for underwater cutting and in the past has been claimed to have advantages for heavy cutting because of the characteristic long flame. Its disadvantage is its relatively low Btu. value per cubic foot. In underwater cutting its usefulness lies in the fact that it can be safely compressed to the pressures necessary to overcome water pressures at depths at which salvage operations are undertaken.

Propane.—This gas is being used regularly in a number of plants because of its relatively low cost in large quantities where it is also used for other purposes and its high Btu. value per cubic foot. However, for proper combustion propane requires about four to five times its volume of oxygen, to some extent offsetting the economic benefits derived from its initial low cost.

Natural Gas.—In localities where natural gas is available, it is often used as a fuel for the preheating flames of cutting torches. Its characteristics as a fuel gas for oxygen-cutting operations are much like those of propane; and the same cutting tips are generally used for both.

City Gas.—City gas has been widely used in a few industrial regions, where economic factors are favorable. Because of the lower flame temperature oxy-city gas cuts in thin materials are likely to be smoother and sharper than oxy-acetylene cuts. The speed of cutting with city gas as compared with acetylene is somewhat slower. Low calorific value and low flame temperature account for the high consumption of city gas necessary in oxygen cutting.

Except for acetylene, hydrogen and propane, the usual fuel gases involve a mixture of several constituents.

Effect of Oxygen Purity

Only oxygen of the very highest purity should be used for cutting operations. The influence of what might otherwise be regarded as trivial amounts of impurities is illustrated by Figs. 4 and 5. It will be observed from Fig. 4 that the decrease of oxygen purity from 99.5 to 98.5 will, on the average, necessitate an increased oxygen consumption of about 25%. The fact is that oxygen cutting of steel involves one of those chemical processes which tend to be self-propagating but in which there is not a great deal of heat developed in the reaction at any given point beyond that which is necessary to raise adjoining regions to the kindling temperatures. It is typical of such reactions that small changes in concentration, or purity, of one of the constituents, result in very great variations in the speed of the reaction.

Metallurgical and Physical Effects of Oxygen Cutting

As explained previously, a quantity of heat is liberated in the kerf when steel is cut with the oxygen jet. Much of this heat is transferred to the walls of the kerf and as a result the metal for an appreciable depth adjoining the cut surface is heated rapidly to a temperature well above the critical range. But as the cut progresses and the source of heat moves on, the mass of cold metal near the cut acts as a quenching medium and rapidly cools the heated metal. The phenomenon is in some respects similar to that of the usual heat-treating operation. A piece of steel, heated to above the critical tem-

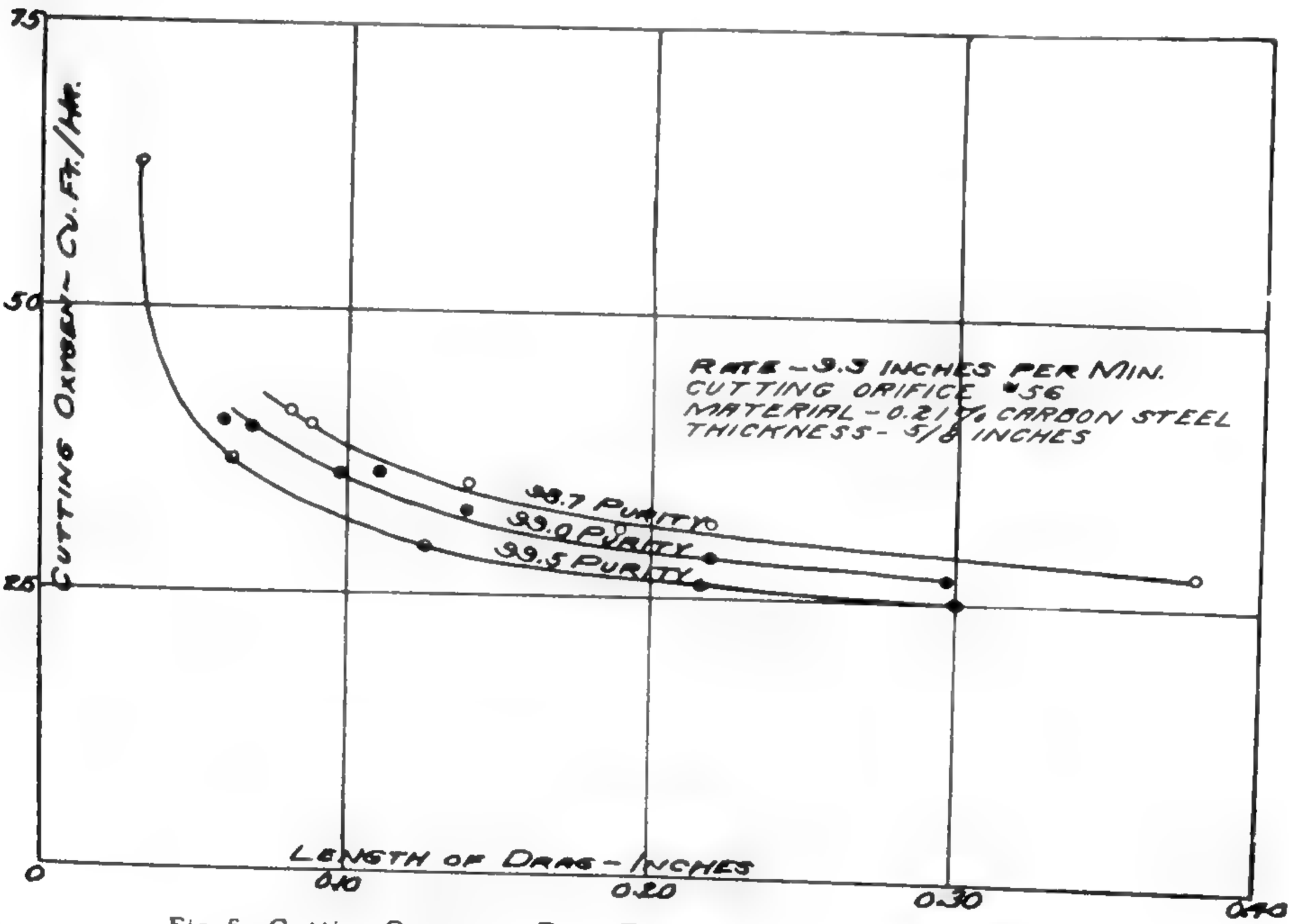

Fig. 5—Cutting Oxygen vs. Drag, For Various Degrees of Oxygen Purity

perature range and rapidly cooled, will harden and the degree of hardening will depend to a large extent on the amount of carbon and alloying elements present in the steel, and also on the rate of cooling.

2. The hardening effect on carbon steels containing 0.25% carbon or less is negligible for most practical purposes.

3. The higher carbon and alloy steels are hardened to a greater degree than the lower carbon and unalloyed steels.

4. The hardness effect progressively decreases away from the cut.

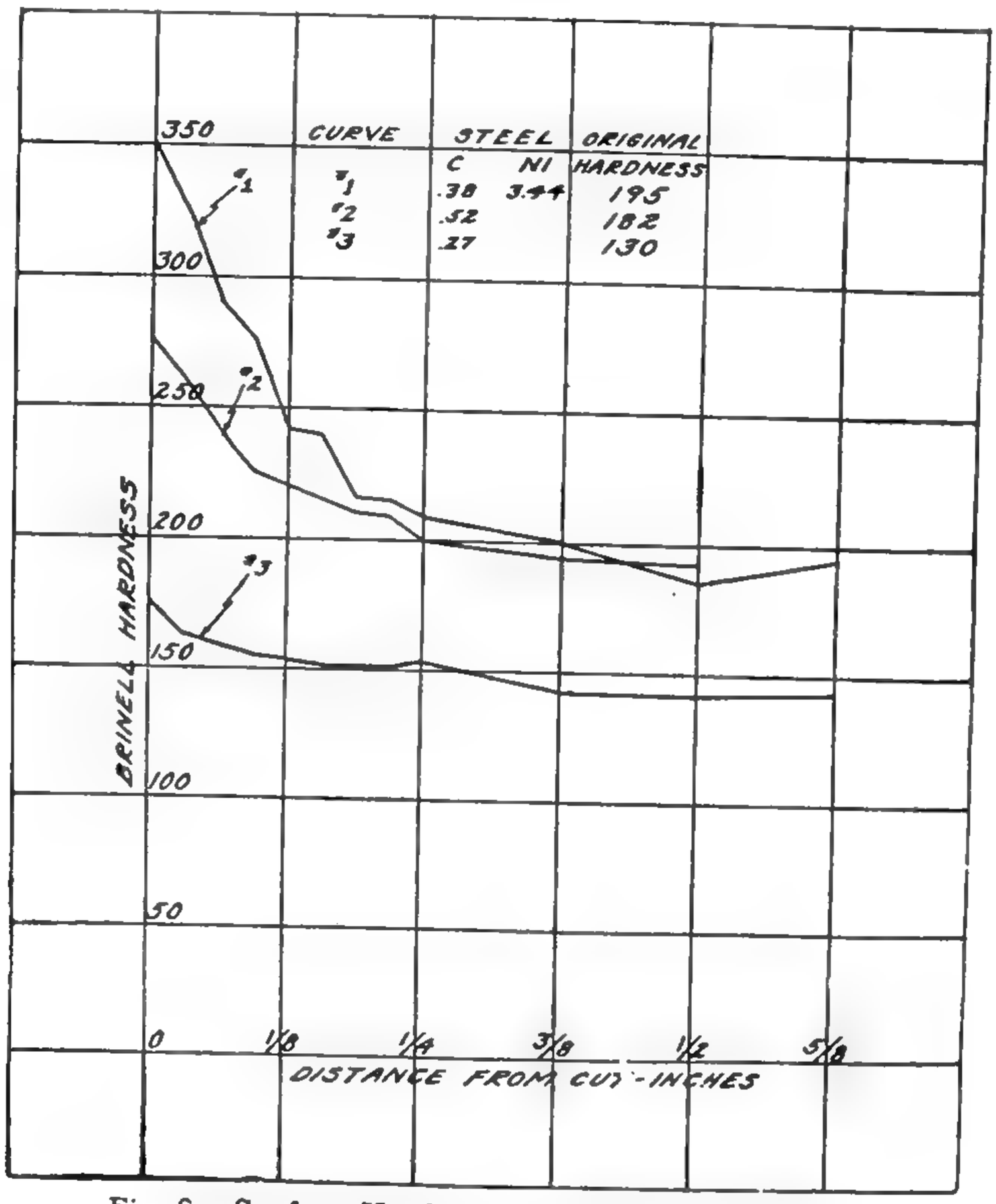

Fig. 6.—Surface-Hardening Effect (6½-In. Billets

A rapid quench from a high temperature will result in a hardened steel. This is the condition brought about at the face of the cut where the temperature of the cutting operation has been high enough to raise the metal well above the critical or transformation temperature range and where this heated zone is bounded by large masses of relatively cold metal, which in turn act as the quenching medium. (See Chapter 3 for information on the metallurgy of steel.)

A study of Fig. 6 brings out four important facts:

1. The heat released in cutting penetrates to a measurable distance and raises the temperature sufficiently to produce subsequent hardening. In this particular instance the penetration is approximately $^{1}/_{8}$ to $^{3}/_{16}$ inch.

A metallographic examination of the hardened area shows that for the lower carbon steel the pearlitic structure normal for most steels in the annealed state has been converted into sorbite (or into troostite if the carbon content is high enough), and that the same constituents with the addition of martensite are obtained in the case of the higher carbon and alloy steels. Moreover, as illustrated by Fig. 7, the zone between the face of the cut and the unaffected metal at a distance from the cut reveals more or less of the original grain structure. The obvious explanation is that the metal was not held sufficiently long at temperatures above

the transformation temperature to permit complete transformation to austenite. It is because the austenitic transformation was incomplete that it was not possible when the metal was subsequently chilled to develop fully the sorbitic and troostitic structures. This is probably the primary explanation for the progressively decreasing hardness inward from the face of the cut, although some increased hardness at the face of the cut may be due to the fact that there is quenching from a temperature higher than the temperatures inward from the face.

It has been clearly shown that the effect of oxygen cutting does not extend to a very great depth. With thicknesses as great as 30 in., it extends to a depth of the order of $^{3}/_{8}$ inch. However, as indicated by Fig. 6 the depth of hardening when cutting 6-in. low-carbon steel is only about $^{1}/_{8}$ in., although it may be as much as $^{1}/_{4}$ in. with higher carbon and alloy steels. For $^{1}/_{2}$-in. material the depth of the affected zone in low-carbon steel is only about $^{1}/_{32}$ in. (see Fig. 8). For lighter thicknesses it is even less. If actually required, much or even all of the hardened surface metal may readily be removed by machine tools. If a machine finish is not necessary, however, and the cutting has been done with sufficient accuracy, the affected metal need not be removed, except possibly in the case of the higher carbon steels and alloy steels.

Bending and tensile tests made with specimens prepared from structural steel containing less than 0.25% carbon, by oxygen cutting, shearing and friction sawing, have shown the damaging effect of the latter two methods to be generally far more pronounced than that of oxygen cutting.

Figure 8 gives some indication of what may be expected with $^{1}/_{2}$-in. steel that has been sheared, friction sawed or machined as compared with typical examples of oxygen cutting. It will be seen that the oxygen-cut edge is in much better condition than that produced either by shearing or friction sawing. Metallographically it is superior to the unaffected metal or the machine-cut edge because it is characterized by the relatively tough sorbitic structure which has characteristics superior to pearlite, the prevalent constituent in annealed or air-cooled steels of the low-carbon type.

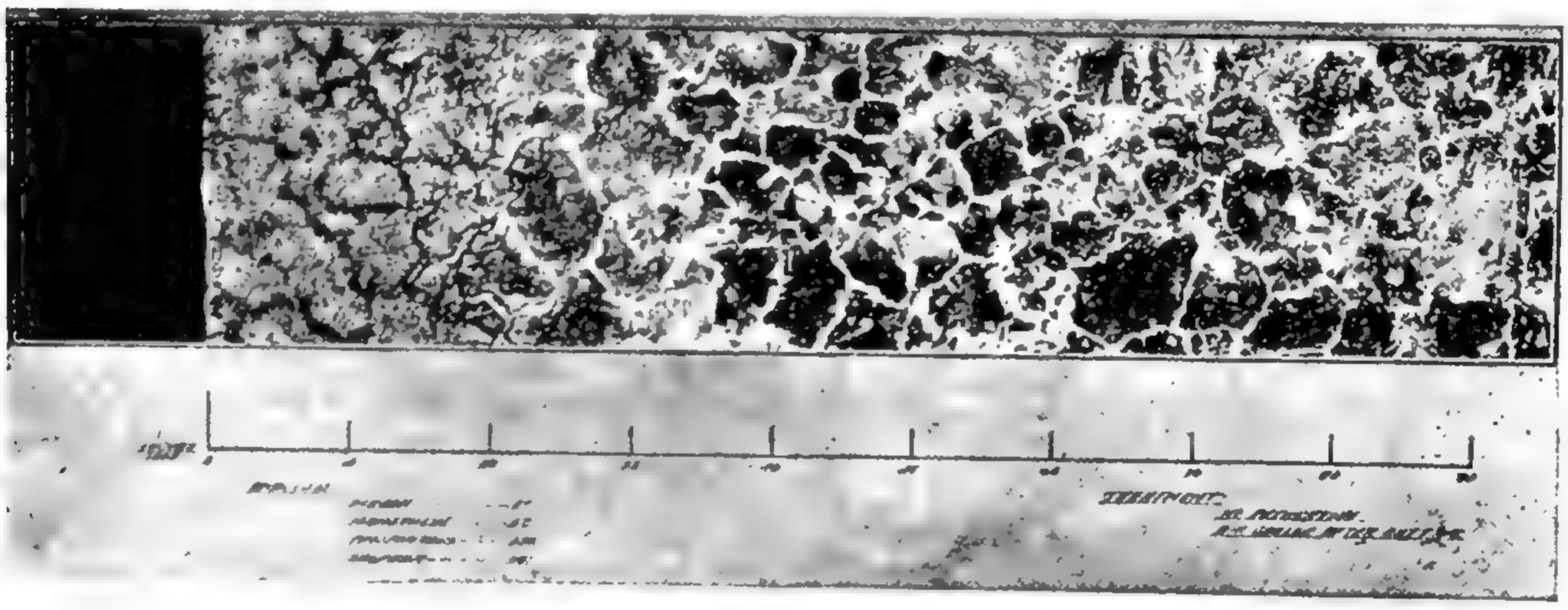

Fig. 7.—Effect of Oxygen Cutting on Microstructure

From the foregoing it is evident that for lower carbon steels there is no question that the oxygen-cut surface is at least equal in physical properties to the unaffected metal and most codes recognize this fact. For example, the *ASME Boiler Code* merely specifies that "the edges must be uniform and smooth and must be freed of all loose scale and slag accumulations before welding." It further states that "the discoloration which may remain on the flame-cut surface is not considered to be detrimental oxidation." The Boiler Code does not, however, permit welding oxygen-cut surfaces in steel of over 0.35% carbon content. This is because with the higher carbon content there is a tendency for the cut edge to develop minute cracks. For ordinary work, these minute cracks can be prevented by proper preheating.

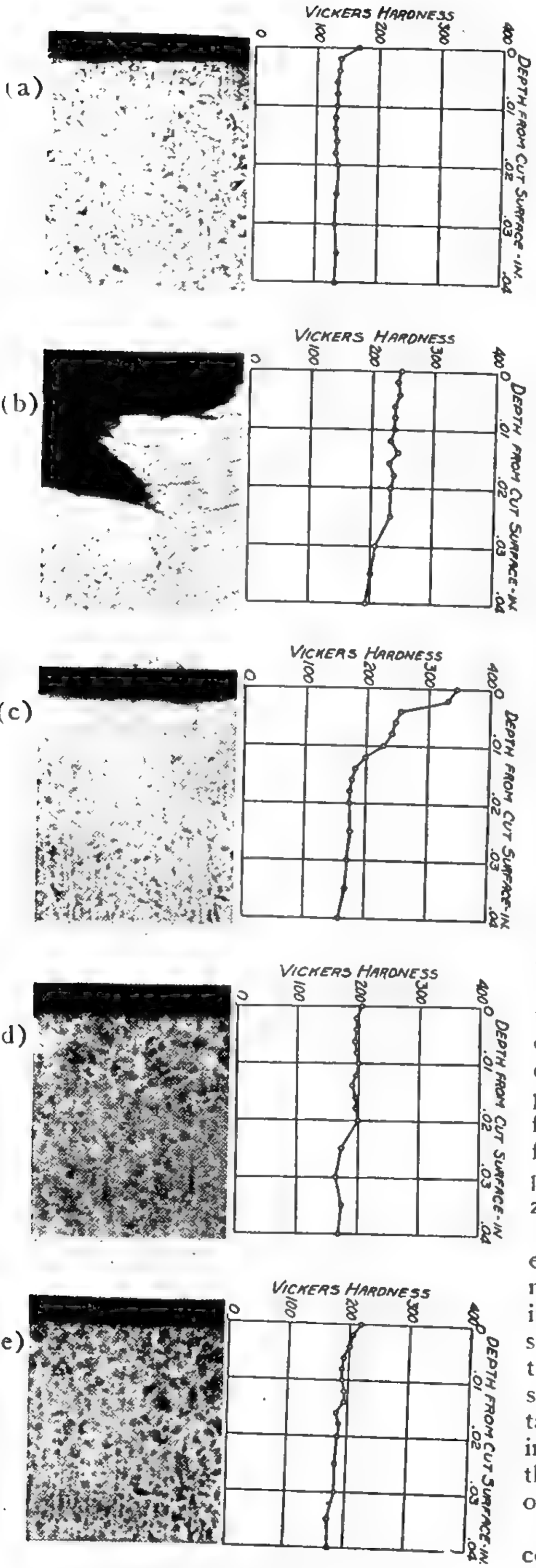

Fig. 8.—Effect of Cutting Procedures on Surface Hardness and Microstructure

Reading from top down in Fig. 8, the surfaces illustrated are produced by the various cutting procedures and show:

(a) Machined surface
(b) Sheared surface
(c) Friction-cut surface
(d) Manual oxygen-cut surface
(e) Machine oxygen-cut surface

Chemical Effects of Oxygen Cutting

In addition to the purely metallurgical changes due to oxygen cutting there are chemical changes which extend to a slight depth. Samples taken from near the cut surface of carbon steels show a slightly higher carbon content than samples taken at a greater depth. The increase in carbon near the surface occurs regardless of whether the preheating flames are fed by a gas containing carbon, such as acetylene, or by a carbon-free gas, such as hydrogen. It would appear that the increase in carbon is brought about, at least in part, by migration of carbon from the colder metal to the hotter metal. Several investigators have found that the carbon content is actually slightly lower a moderate distance in from the face of the cut than it is in the unaffected zone at a distance from the cut (see Fig. 9). It appears logical, therefore, to conclude that the increased carbon content at the face of the cut may have been derived from the region of abnormally low carbon content. A carbon migration toward the face could presumably be the result of carbon enrichment effected by the progressive precipitation of ferrite which advances from more remote regions toward the face of the cut because of the higher temperatures attained closer to the cutting zone.

There are, however, two other possible explanations. One is that some carbon may be absorbed from the hot metal being oxidized in the cut. The other is somewhat similar, viz., that the action of the oxygen jet at the face of the cut is such that the ferrite is more actively attacked than is the cementite and that the increased carbon content is derived from the latter. This, however, is probably only a minor factor.

Nickel acts similarly to carbon in concentrating at the surface of the cut; chromium and copper do the opposite, while manganese and silicon are not ap-

preciably affected. These effects are minor.

Effects of Alloying Elements

Alloying elements have two possible effects; first, they may increase the resistance of the steel to the cutting; and, second they may give rise to hardened cut surfaces. The first effect is roughly evaluated in Table 1.

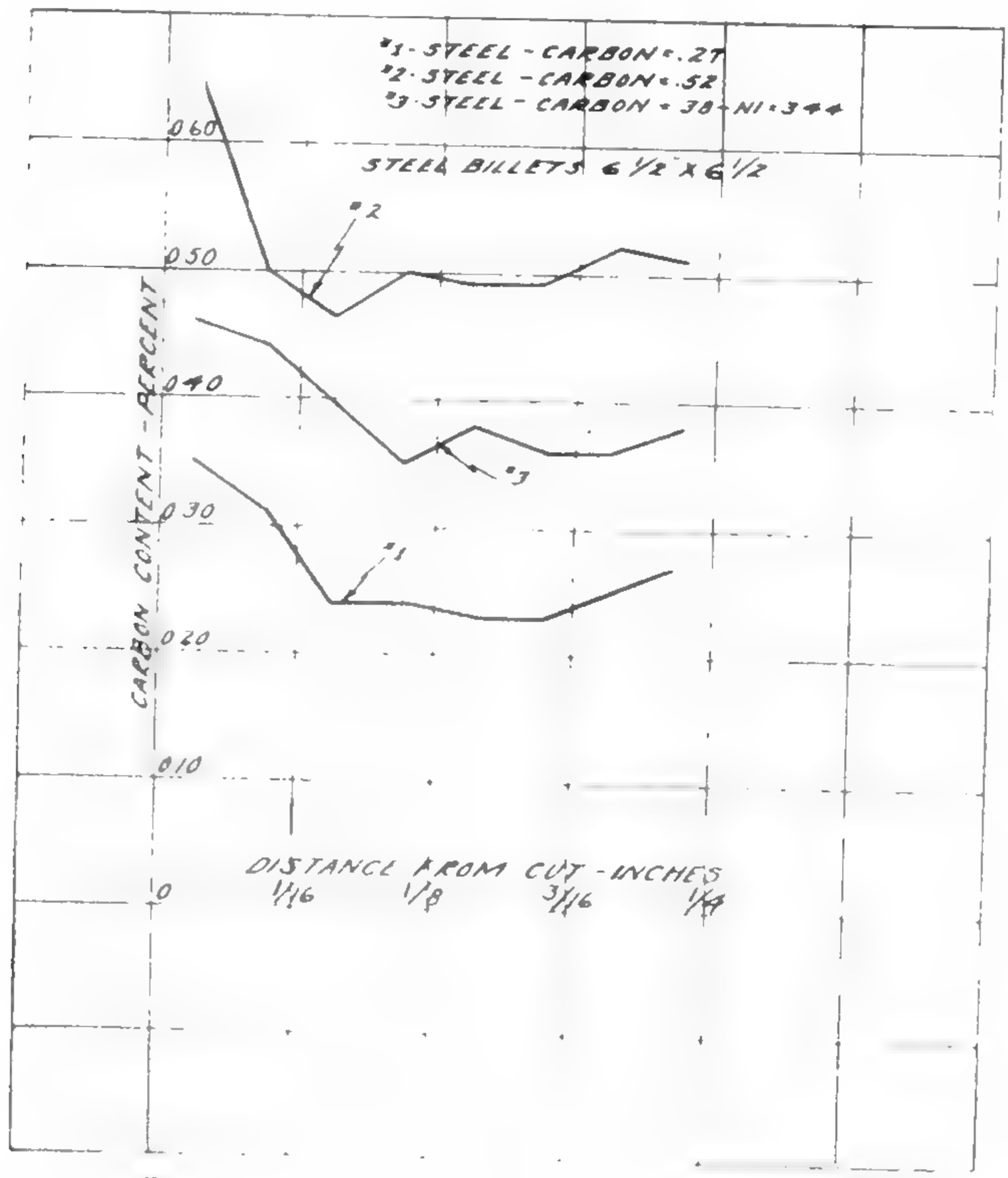

Fig. 9.—Carbon Content vs. Distance from Cut

Heat Treatment

Plain-carbon steels containing 0.25% carbon or less are not, as a rule, subject to hardening or cracking as a result of temperature changes due to oxygen cutting, except for heavy sections or castings.

As the carbon content increases or alloys are added, steels become more and more responsive to heat treatment; that is, they become harder when suddenly cooled from above the critical range. Being harder, they are more brittle and more likely to crack from strains set up by cooling stresses. It is therefore advisable to preheat these steels before oxygen cutting. In fact, for steel having a carbon content over 0.25% or any alloy that is hardenable, preheating should always be employed. The need for preheating is greater for the heavier sections than for the lighter sections and becomes a requirement when heavy sections are to be cut to intricate shapes. With such shapes having acute angles where high stress concentration will be involved, it is particularly desirable to preheat and stress relieve.

Preheating accomplishes several useful purposes:

1. It increases the efficiency of the cutting operation by reducing the amount of oxygen and fuel gas required to make the cut.
2. It reduces the temperature gra-

dient set up by the cutting operation. This in turn reduces or gives more favorable distribution of the cooling stresses, thereby preventing the formation of quenching or cooling cracks. Distortion is also reduced.

3. It reduces the hardness of the cut surface by reducing the rate of cooling.

4. It reduces the carbon and nickel migration toward the cut face by lowering the temperature difference between the cut face and the body of the metal.

Table 1—Effect of Alloying Elements on Resistance of Steel to Oxygen Cutting

Element	Effect of Element on Oxygen Cutting
Carbon C	Steels up to 0.25% carbon can be cut without difficulty. Higher carbon steels should be preheated to prevent hardening and cracking. Graphite and cementite (Fe_3C) are detrimental but cast irons containing 4% carbon can be cut by special techniques or processes, described in later pages of this chapter.
Manganese Mn	Steels of about 14% manganese and 1.5% carbon are cut with difficulty and for best results should be preheated.
Silicon Si	Silicon in amounts usually present has no effect. Transformer irons containing as much as 4% silicon are being cut. Silicon steel containing considerable amounts of carbon and manganese must be carefully preheated and post-annealed for best physical properties.
Chromium Cr	Pure chromium reacts with oxygen only when at very high temperatures. Steels up to 5% chromium are cut without much difficulty when the surface is clean. Higher chromium steels, such as 10% chromium steels, require special technique (see section on Cutting of Materials of Poor Cuttability) and the cuts are rough when the usual oxy-acetylene cutting process is used. In general, carburizing preheating flames are desirable when cutting this type of steel. The recently developed flux injection and iron powder cutting processes, described in a later section, enable cuts to be readily made in the usual straight chromium irons and steels as well as in stainless steel.
Nickel Ni	Amounts up to 20 or 30%, if the carbon is not too high, may be cut with the conventional oxy-acetylene process; up to about 7% nickel content, cuts are very satisfactory. Cuts of excellent quality may be made in the usual engineering alloys of the stainless steels (18–8 to about 35–15 as the upper limit) by the flux injection or the iron powder cutting processes.
Molybdenum Mo	This element affects cutting about the same as chromium. The pure metal is difficult to cut. Aircraft quality chrome-molybdenum steel offers no difficulties. High molybdenum-tungsten steels, however, may be cut only by means of special technique.
Tungsten W	The pure metal may be cut if heated to a sufficient temperature. The usual alloys up to 12 or 14% may be cut very readily, but cutting is difficult with a higher percentage of tungsten. The limit seems to be about 20% tungsten.
Copper Cu	In amounts up to about 2%, copper has no apparent effect.
Aluminum Al	Unless present in large amounts (on the order of 10%) the effect of aluminum is not appreciable.
Phosphorus P	This element has no effect in amounts usually tolerated in steel.
Sulfur S	Small amounts, such as are present in steels, have no effect. With higher percentages of sulfur, the rate of cutting is reduced and sulfur dioxide fumes are noticeable.
Vanadium V	In the amounts usually found in steels, this alloy may improve rather than interfere with cutting.

In practice the temperature used for preheating varies from 200 to about 1300° F. The tendency among those who have had much experience in this direction appears to favor the lower temperatures (generally below 600° F.) rather than the higher temperatures. When the temperature is too high, particularly if it exceeds 1200 or 1300° F., it is more difficult to make smooth cuts, even though very high cutting speeds may be reached. (Refer to the section on Cutting at Elevated Temperatures for a discussion of the factors involved when the base metal is maintained at a temperature in excess of the usual preheat temperatures.) The higher the temperature, the more rapid is the reaction of the oxygen with the iron; it is, therefore, possible to cut faster when the metal is preheated. But it is essential that the temperature be fairly uniform, for if the outside of the metal being cut is at a lower temperature than the interior, the oxidation reaction will proceed more energetically in the interior than at the top and bottom. The result is often the formation of large pockets in the interior that will either give rise to an unsatisfactory cut or to such slag pollution at lower levels that it will be impossible for the oxygen stream to completely penetrate the steel. Consequently, it is important that the cutting be effected as

soon as possible after the material is removed from the preheating furnace.

If, through lack of facilities, preheating should prove impracticable, the stresses incident to cutting may be reduced appreciably, in the case of very light cutting, by passing the cutting torch, with the preheating flames lighted and the cutting oxygen turned off, slowly over the line of the cut until the metal in this region is raised to the approximate temperature desired. While one such pass may suffice, two or more passes generally yield better results. Another method which gives even better results is to preheat the metal by means of an auxiliary multiflame heating tip so mounted as to precede the cutting tip.

ing straight up and down rather than dragging back so far that a large (lower) corner is not cut. When the drag is so short that no uncut corner is left, the cut is often referred to as a *drop cut.* The left hand sketch of Fig. 10 shows a 0.11-in. drag with lower corner completely severed; center illustration shows 0.20-in. drag with corner completely severed; right illustration shows a 0.22-in. drag and lower corner not completely severed. (Fracture in lower left-hand corner not clearly revealed by photograph.)

2. Sufficiently smooth sides of cut; i.e., not grooved, fluted or ragged.

3. Satisfactory slag condition. For most production work there should be no firmly adhering slag that is difficult to remove.

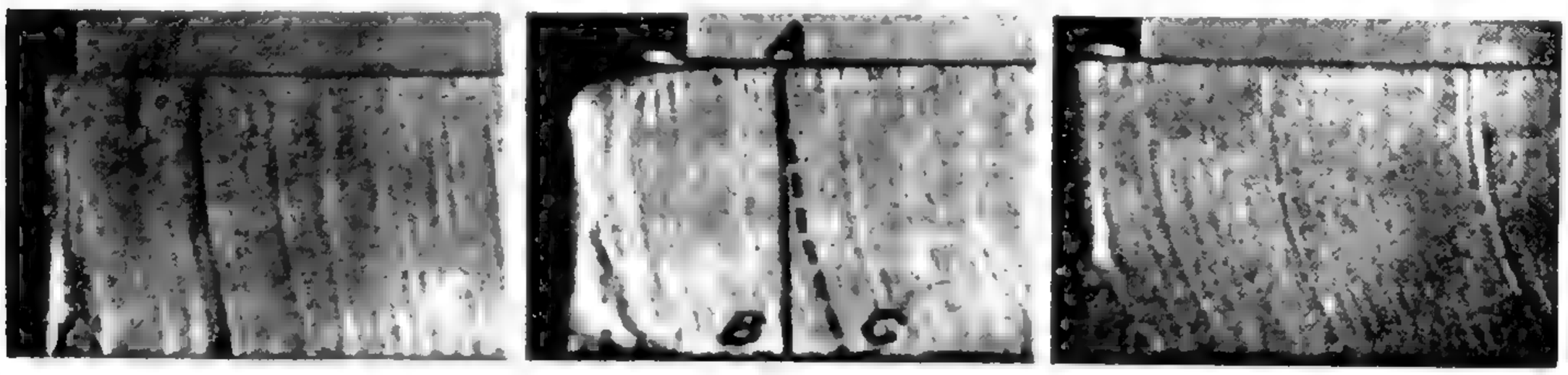

Fig. 10.—Specimens of 1-In. Cuts

To avoid, or at least greatly minimize, the internal stresses set up in the steel by the oxygen-cutting process, it is possible to utilize the annealing, normalizing or stress-relieving processes subsequent to the cutting operation. These heat-treatment processes are discussed in detail in Chapter 43. By proper postheat treatment, all traces of the metallurgical changes caused by oxygen cutting will be eliminated. If a furnace is not available to carry out the heat treatment, or if because of size it should prove impracticable to use a furnace, the cut surface usually may be reheated to the proper temperature by means of multiflame heating tips.

Quality of Oxygen Cutting

It is necessary to define carefully and have a clear understanding of the phrase *quality of the cut.* A satisfactory commercial cut may be defined as one fulfilling the following requirements:

1. A sufficiently short drag; that is, the line markings on the face of the cut should approach the condition of be-

4. The upper edges of the cut should be sufficiently sharp for the requirements of the particular job. The term *melt down* is often used to refer to the condition when the preheating flames have caused the upper edges of the cut to become molten, thereby losing the sharpness requisite in a quality cut.

The first two requirements mentioned, viz., length of drag and smoothness of cut, are generally of greater practical importance than the other two, and of these two, the length of drag is of greater fundamental importance. In fact, length of drag alone may be used as the criterion for obtaining the most economical cutting conditions. In general the requirements for a sufficiently smooth cut, satisfactory slag condition and sharp edges will also be fulfilled adequately for the majority of applications.

The ten most important variables that affect oxygen cutting are as follows:

1. Size of cutting orifice.
2. Oxygen operating pressure.
3. Speed of cutting.
4. Thickness of the material being cut.

5. Quality of the material.
6. Purity of the oxygen.
7. Intensity of the preheat.
8. Angle of incidence of the cutting stream to the upper edge.
9. Smoothness of cutting orifice.
10. Cleanliness of the end of the tip.

The rate of oxygen consumption must be thought of as dependent upon the first two of these variables and not as a separate independent variable.

For any given cut each of the variables listed should be so evaluated that the precise quality of cut desired may be realized with the minimum aggregate cost in oxygen, fuel gas, labor and overhead.

Another factor to be considered along with the quality of the cut is the precision with which oxygen cuts can be maintained. When the torch is held rigidly and advanced at constant speed, as in machine-guided oxygen cutting, across-the-cut tolerances may be maintained within narrow limits. In ordinary steel of 6 in. thickness, cut surfaces can be held true as to cross-sectional squareness, within $^1/_{32}$ inch. Cuts in thinner sections can be held within proportionally smaller limits. The degree of longitudinal precision of a machine-guided torch cut depends on the trueness of the guide rails of the cutting machine, the clearances in the operating mechanism and the uniformity in speed of the propelling unit. Machine-guided torch cuts are frequently so smooth and square and have such sharp edges that they require no further finishing of any kind.

It is impossible to attempt high precision shape cutting without an accurate knowledge of kerf widths. It is not practical, however, to present data on kerf widths in this particular treatment because the widths not only vary considerably with the operating pressure, speed of cutting, etc., but are primarily dependent upon the particular cutting orifice employed. It is therefore advisable that such information be gained by direct observation. Care should be taken not to generalize such data because kerf widths are specific to the particular cutting conditions involved. For example, it will be found that the kerf is affected by the distance of the tip from the upper surface of the material. The tendency is for wider kerfs to result when the tip separation is increased.

Precision shape-cutting also demands that attention be given to the question of thermal expansion. Lack of precision may result either from warpage of the material in the event that thin sheet or plate stocks are involved, or it may result from a shifting of the plate during progress of the cut as a result of the heat of the cutting operation. One should, therefore, carefully plan the operation so as to minimize these effects. For instance, it is desirable to eliminate if possible, narrow sections of metal that may become overheated.

Buckling and warping can often be minimized. When trimming both sides of a plate, warpage will be lessened if two torches are mounted one on each side so that both cuts are made simultaneously and in the same direction. Distortion can often be controlled in making irregular cuts in plates by inserting wedges appropriately in the kerf following the cutting torch to limit the expansion of the metal. In cutting openings in the middle of a plate, it may be found advantageous from the standpoint of distortion to make a series of unconnected cuts leaving the *cut out* attached to the plate in a number of places until the cut has been almost completed; the connecting parts are then cut through last. Thin gage material is often stack cut, thereby not only increasing production but also eliminating warping and buckling. Thin plate has also been cut under water to remove the heat caused by the cutting and thus prevent distortion.

EQUIPMENT USED

Manual

Cutting equipment for manual and machine cutting is identical in the respect that in all cases the gases from the supply source are fed through suitable regulators to provide a steady pressure and introduced to the torch. In the torch, the gaseous preheat fuel is mixed with the correct amount of oxygen and the mixed gases are burned at the tip to provide the preheat. At the same time, the major portion of the oxygen is conducted through a quick opening valve to the cutting orifice, from which it issues, as required, at high velocity to cut the steel at which it is directed.

For manual cutting a torch which can be readily manipulated by hand is used.

Modern torches are equipped with separable tips in which the oxygen-cutting jet is surrounded at a proper distance by the preheating flames (see Fig. 3). Tips of different sizes may be readily interchanged in the head of the torch to provide a range of orifice sizes, intensities and disposition of preheat flames as required to meet different cutting conditions and to provide the maximum amount of flexibility in the application of the torch. For example, for rusty or scaly steel a tip furnishing a heavy preheat would be selected, yet it can be installed in a standard cutting torch thus increasing the versatility of the torch.

Torches are of two types: first, those in which the preheat fuel and oxygen for the heating flames are mixed in the tip, called a *mixer type*; and second, those in which the mixing takes place in the head or at some location back of the head, as for example, in the body of the torch. This latter type is designated as a torch of the *premixed type.* If both the oxygen and fuel gas are under appreciable pressure the torch or blowpipe is designated as a *positive pressure torch* and when the fuel gas is at a lower pressure, generally a fraction of a pound per square inch, and supplied to the flames through the aid of an injector, the torch is designated as a *low-pressure* or *injector torch.*

The torch is connected to the gas supply by hose lines of sufficient size to conduct the volume of gases necessary for the cutting operation without excessive pressure drop. The hose lines are in turn connected to the outlet of the two pressure regulators (one for the fuel gas and one for the oxygen), which in turn are connected to the respective gas supplies, which may be from pipe line, manifold or cylinder. (Small portable acetylene generators are used for small installations as a source of acetylene supply.)

Machine

Oxy-acetylene shape-cutting machines can be divided into two classes: portable and stationary. As the name implies, the portable machine may be taken to the work, while the stationary type is fixed in location and is generally served by a crane.

Portable machines are used predominantly for straight line cutting, although they can be adapted for circular cutting. The carriage supports the torch in an adjustable mounting, and is driven by an electric motor. Usually the machine travels on a straight section of track, which performs the function of guiding the torch along the line of the cut. The electric motors used for these machines are capable of adjustment over a wide range of speeds so that uniform speeds of travel may be realized, and so that the particular speed required for the cutting operation may be selected. For these machines the degree of precision longitudinally along the line of the cut depends mainly on the accuracy of the guide rails as well as upon the clearances of the operating mechanism. These machines find wide use in the preparation of plate for welding, since the torch can readily be adjusted to cut a bevel, as well as to make a square cut; also for ripping plate, and other purposes requiring a straight-line cut.

The stationary type of cutting machine is designed on two general mechanical principles. One is the pantograph design, while the other employs a cross-carriage mechanism. Both designs can cut regular or irregular shapes of practically any complexity and of almost any size. These machines mount as many as six torches and are used to cut the same number of identical shapes simultaneously on a production basis. They are motor driven, and are designed to follow an outline, or template, of the part to be cut. The tracing device may be manually guided around the outline of a drawing of the part, or a tracer may be used that follows a vertical strip, shaped to size and similar to a cookie cutter. A magnetic tracer having a magnetized roller, which adheres to and follows a steel template automatically is used on some machines, while a further refinement is an electronic tracing device, in which a spot of light automatically traces the outline of a drawing of the part to be cut.

To extend the usefulness of all cutting machines, beveling devices may be used as auxiliary equipment. These torches are attached to either the carriage of a portable machine, or are mounted in place of the torch on a stationary type. Their main use is for the edge preparation of heavy plate, where a double bevel or double bevel and root face are required. With the beveling device the two bevels and root face may be cut in

one operation with considerable saving in time and labor.

Auxiliary Equipment

The auxiliary equipment used in both manual and machine cutting consists of the apparatus necessary to conduct the gases from the supply source to the point of application, i.e., the torch.

The regulators used for cutting operations are essentially similar to those used for welding operations, and which are described in Chapter 4 of this HANDBOOK. In fact, for light cutting operations, especially those in which a cutting attachment is used with a standard welding torch, identical regulators would be employed. However, for the majority of cutting operations the oxygen consumption is large, making it essential to use a regulator capable of supplying large flows at the correct pressure.

Hose should be selected having a capacity large enough to handle the volume of gases without undue pressure drop. Hose should be maintained in good condition at all times, and damaged or abraded hose should be scrapped immediately and replaced. Long lengths of hose are to be avoided wherever possible, and couplings and other restrictions in the line should be kept to a minimum to eliminate the pressure loss through them and to avoid the possibility of gas leaks at the joints. The hose should be firmly attached to the torch using standard hose glands and nuts.

For heavy cutting where exceptionally high gas flows are encountered, or for an extended job requiring uninterrupted cutting, it may be necessary to manifold the gas cylinders to provide an adequate gas supply. For large cutting machines equipped with several torches, manifolds are essential, or the gas supply may be from pipe lines, in turn supplied from acetylene generators and a bulk oxygen delivery system.

For the flux injection and the powder-cutting processes used for cutting materials of poor cuttability, described in some detail later in this chapter, auxiliary equipment for introducing the flux or powder into the cutting area is required. One style of equipment consists of a pressurized hopper which holds the flux or metallic powder and by a vibrating unit dispenses it at a metered rate into the cutting-oxygen stream in which it is entrained and thus carried through the torch where it issues directly into the kerf along with the cutting-oxygen stream. In another system the powder is dispensed from the hopper by an ejector and is carried, entrained in a separate carrier gas stream, through a separate hose to the torch and tip where it is mixed with the cutting-oxygen stream, and is thus directed into the area of cutting action.

COMMON APPLICATIONS

Manual Cutting

Manual cutting, in which the cutting torch is held and guided along the workpiece by the operator, was the first method of application of the oxygen-cutting process, and even today it constitutes one of the principal means of application. For manual cutting, the torch is held firmly with the right hand gripping the handle in such fashion to permit operation of the cutting-oxygen lever or trigger by the same hand, the left hand being used to steady the torch head and maintain the relative position of the tip with respect to the work. Hence, successful results depend mainly upon operator skill and proficiency in guiding the torch correctly while maintaining the proper forward motion. However, the operation is relatively simple, and a conscientious workman can become a competent cutting operator with a minimum of practice. Practice alone is the only means by which an operator can acquire the skill necessary to hold the torch at right angles to the work yet at a constant distance from it and at the same time to advance the torch steadily without wavering along the line of the cut. Careful observation of the cutting action, and particularly of the slag flow and drag, enables the operator to correct abnormal conditions while the cut progresses.

In addition to the purely manual process in which the torch is held and guided by hand, manual cutting also includes those operations in which an auxiliary device is employed to help guide the torch and maintain the tip separation from the work. The simplest of such guiding mechanisms is a straight bar or straight edge along which the torch head is drawn for straight line cutting. Another device employed for a similar pur-

pose consists of an assembly with two small wheels which attach to the torch head. In operation the wheels rest on the surface of the work, and can be rolled along the line of the cut. A more specialized device is the circle-cutting attachment, which consists of a radius rod clamped to the torch head, and a center point which may be adjusted for the radius of the circle to be cut. The center point is located in a punch mark on the plate, and the torch is then guided around this center at a constant radius. By such means circles may be cut with good accuracy.

In all oxygen cutting, many variables affect the adjustment of the operating pressures and speed of travel. In manual cutting one of the important factors difficult to evaluate is that of operator skill. Items such as the equipment being used and its condition, the thickness, analysis and cleanliness of the material being cut, will all influence the pressure settings and speed of travel employed. However, as a rough guide for mild steel, not preheated, Table 2 may be used for the initial adjustments, and final adjustments may be made based on experience with the actual operation.

instance, a fairly wide range of oxygen-cutting pressures has been given. It must be realized that these values are based upon average practice. If long lengths of hose are used, or if restrictions in the form of couplings are placed in the line, the required pressures will be affected markedly.

Machine Cutting

The obvious advantage of mechanically guiding the cutting torch was early recognized as a means for improving the results of oxygen cutting. By mechanizing the operation as far as practicable it has been possible to reduce the human factor, which is one of the most serious variables affecting the quality of the cut. By using machines to move and guide the torch the operator can devote his attention to the observation of the cutting operation and can adjust the machine as necessary. It is thus only necessary with the more fully automatic machines for the operator to watch the drag and the flow of slag to be sure the oxygen stream does not pocket and that the speed is correct to produce the desired smooth cut face. Thus, it has been possible to put oxygen cutting on a

Table 2—Data For Manual Cutting of Clean Mild Steel (Not Preheated)

Thickness of Steel, In.	Diameter of Cutting Orifice, In.	Oxygen Pressure, Psi.	Cutting Speed, In./Min.	Gas Consumption, Oxygen, Cu. Ft./Hr.	Gas Consumption, Acetylene, Cu. Ft./Hr.
1/8	0.0200–0.0400	15–30	20–30	18–55	6–9
1/4	0.0310–0.0595	11–20	16–26	37–93	7–11
3/8	0.0310–0.0595	17–30	15–24	47–115	7–12
1/2	0.0400–0.0595	20–31	12–22	66–125	10–13
3/4	0.0465–0.0595	24–35	12–20	117–143	12–15
1	0.0465–0.0595	28–40	9–18	130–160	13–16
1 1/2	0.0595–0.0810	30–45	6–12	150–225	15–20
2	0.0670–0.0810	22–50	6–13	185–231	16–20
3	0.0670–0.0810	33–55	4–10	207–290	16–23
4	0.0810–0.0860	42–60	4–8	235–388	20–26
5	0.0810–0.0860	49–70	3.5–6.4	281–437	20–29
6	0.0980–0.0995	36–80	3.0–5.4	400–567	25–32
8	0.0995–0.1100	57–77	2.6–4.2	505–625	30–39
10	0.0995–0.1100	66–96	1.9–3.2	610–750	36–46
12	0.1100–0.1200	58–86	1.4–2.6	720–905	42–55

Acetylene pressures have been omitted from the table above, since they depend mainly on torch and tip design rather than on external factors such as thickness of the material. It is therefore recommended that for specific acetylene pressure settings particularly, and also for oxygen pressure values, reference be made to equipment manufacturer's charts for the apparatus being used.

The figures quoted in Table 2 can only be taken as fair average values. For

production basis, and the cutting machines are now regarded in the same light as machine tools in that they are capable of producing high quality cuts with accuracy, dependability and economy.

Cutting machines should be installed so as to avoid jarring and vibration during the cutting operation. The work-holding table should be constructed to hold the work without movement during the cut, and it should be designed to hold the scrap pieces to prevent their falling

and damaging the machine or endangering the operator. If scrap pieces are allowed to fall, it is also conceivable that the machine or work-piece may be jarred, resulting in a poor cut. Adequate space around the machine is required for ease in loading and unloading the machine. The capacity of the gas supply system (manifolds or pipe lines, regulators and hose) should be considered to insure sufficient volume of gases at the required pressures to permit uninterrupted cutting.

In machine cutting, some of the main factors which affect the quality of the cut have been eliminated, and generally more consistent results are obtained. Still, many variables remain; therefore, the chart of recommended pressures and consumptions in Table 3 should be considered as giving only average values to be used as a starting point when selecting settings for a particular job. A few trial cuts on the material should suffice to obtain the actual adjustments to be used.

Table 3—Data for Machine Cutting of Mild Steel (Not Preheated)

Thickness of Steel, In.	Diameter of Cutting Orifice, In.	Oxygen Pressure, Psi.	Cutting Speed, In./Min.	Gas Consumption, Oxygen, Cu. Ft./Hr.	Gas Consumption, Acetylene, Cu. Ft./Hr.
1/8	0.0200–0.0400	15–30	22–32	17–55	5–9
1/4	0.0310–0.0595	11–35	20–28	36–93	6–11
3/8	0.0310–0.0595	17–40	19–26	46–115	6–12
1/2	0.0310–0.0595	20–55	17–24	63–125	8–13
3/4	0.0380–0.0595	24–50	15–22	117–159	12–15
1	0.0465–0.0595	28–55	14–19	130–174	13–16
1 1/2	0.0670–0.0810	22–55	12–15	185–240	14–18
2	0.0670–0.0810	22–60	10–14	185–260	16–20
3	0.0810–0.0860	30–50	8–11	207–332	16–23
4	0.0810–0.0860	40–60	6.5–9	293–384	21–26
5	0.0810–0.0860	50–65	5.5–7.5	347–411	23–29
6	0.0980–0.0995	45–65	4.5–6.5	400–490	26–32
8	0.0980–0.0995	60–90	3.7–4.9	505–625	31–39
10	0.0995–0.1100	70–90	2.9–4.0	610–750	37–45
12	0.1100–0.1200	69–105	2.4–3.5	720–880	42–52

In this table acetylene pressures have been omitted, since these pressures are mainly a function of equipment design and are not directly related to the thickness of the material to be cut. It is suggested that for acetylene pressure settings, the charts of the equipment manufacturer be consulted.

It should be observed in comparing Table 3 with Table 2 that machine cutting has the advantage of being capable of higher speeds with substantially equal gas consumption, resulting in a decided economy.

Pressures and flows given in Table 3 cover a fairly wide range which represents average practice. Pressures may vary considerably since restrictions in the line may require pressures different from those given to provide the gas volume required. In general, pressures are usually reported for hose lengths up to about 25 feet. For longer lengths of hose or for under- or oversize hose, pressures should be adjusted accordingly.

Material thicknesses over 12 in. are in the range covered by heavy cutting, which is treated later on page 537.

Multiple and Stack Cutting

Oxygen cutting is not necessarily restricted to a single torch per operator. In many applications of machine cutting as many as twenty torches are used to cut a like number of identical shapes simultaneously, thereby effecting considerable economies. Cutting by this method is greatly facilitated by making use of a central control station for controlling the gas and oxygen supply to each of the torches. Concentric circles for flanges and the like are cut in one operation, with two or more torches. Stationary type machines having a single tracing head following a drawing or template of the part and mounting the required number of torches are universally used for multiple cutting operations.

In addition to cuts made through a single thickness of material, oxygen cuts may be made through several thicknesses simultaneously (see Fig. 11). This operation is known as *stack cutting* and offers a means of cutting a number of plates simultaneously with a single torch, or even with a multiple torch arrangement for quantity production.

The plates in the stack should be clean and flat, with edges in alignment where the cut is started. The number of plates that make up the stack will vary according to the thickness of the individual plates to keep the stack thickness within proper limits. It should be remembered that the heavy preheat necessary to cut a thick stack may melt down the edges of the top one of a pile of these sheets.

Because of the thinness or composition of some steel sheets, it is sometimes difficult to maintain the cutting action. As an aid in preventing the loss of such cuts, use is often made of a *waster plate*. This plate is placed on top of the stack, and should be of a composition that may be readily cut. The waster plate should be of sufficient thickness so as to prevent the preheating flames of the torch from melting the edges of the uppermost sheet of the stack. When the cutting operation has been completed, the waster plate is discarded.

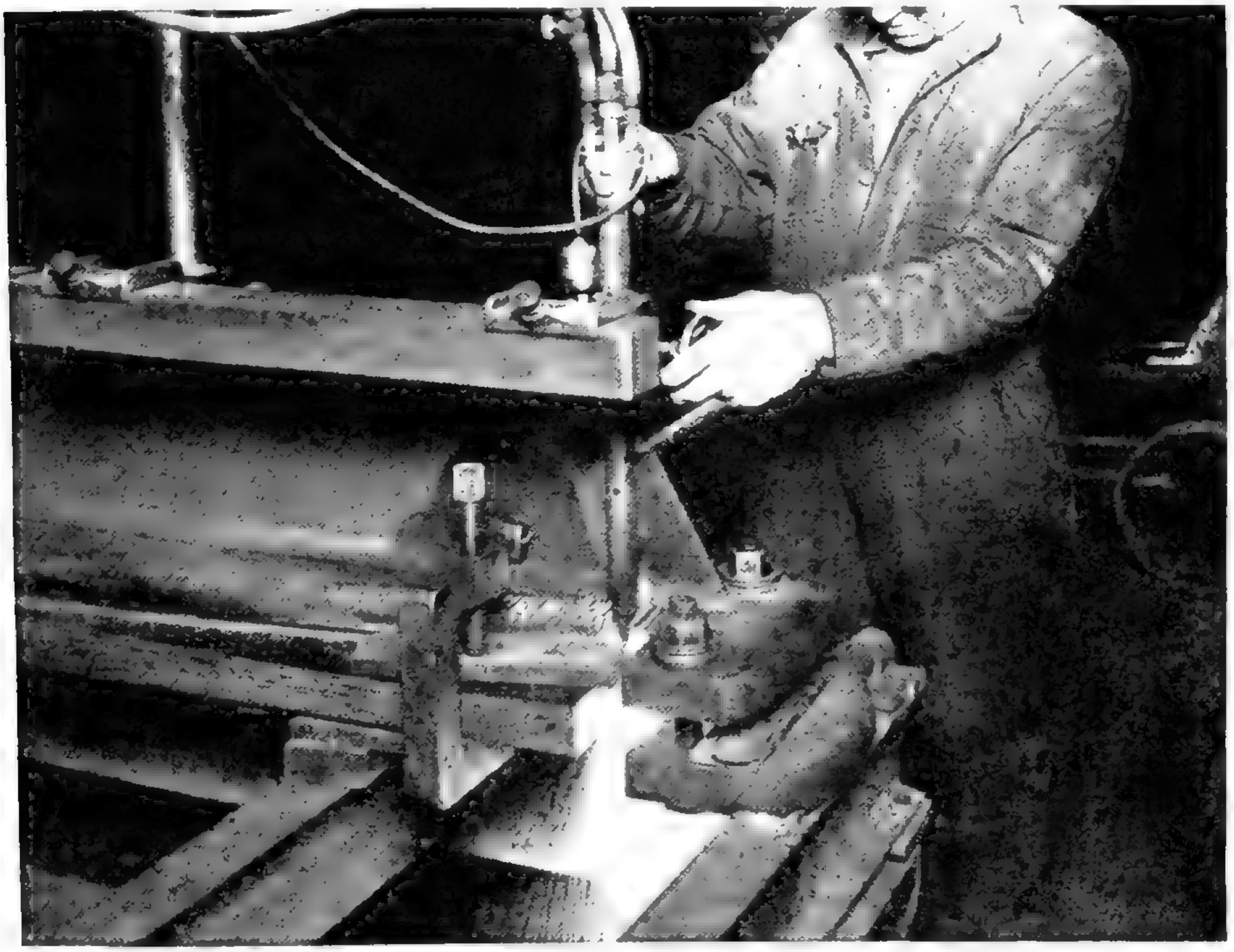

Fig. 11.—Stack Cutting

It is essential that all of the plates or sheets in the stack be in intimate contact if acceptable cuts are to be obtained. To insure good contact the general practice is to use some form of clamping device for bringing the plates together along the line of the cut. The clamping device may be a mechanical device, or a pneumatically operated mechanism. In some instances the plates are welded together instead of being clamped together. This method is usually restricted to stacks composed of thin sheets, and has the advantage that the cut can be started readily at the edge where the plates have been welded together.

The flux-injection and powder-cutting processes have been found to be ideally suited for stack cutting plain carbon and low-alloy steel plates which, because of irregularities in their surfaces, could not previously be successfully stack cut. Also, the degree of clamping can be appreciably less, when using powder cutting, to overcome the effect of voids between plate surfaces on the cutting reaction.

The question of whether to do stack or multiple cutting is largely one of the

economies involved. When the sheets become so large or so thick that clamping costs are higher, multiple cutting provides a ready answer.

Lance Cutting

The time-honored oxygen lance affords a method which may be employed for cutting any of the steels which may otherwise be cut only with difficulty or not at all. Ordinarily, the lance is simply a length of black iron pipe with a valve and proper fitting on one end. A hose large enough to supply oxygen at a high rate of flow from a bank of oxygen cylinders, equipped with a pressure-reducing valve of suitable capacity is attached to the lance. A typical oxygen lance is illustrated in Fig. 12. It is not necessary as a rule that the pipe be very large; in fact, even for quite heavy operations a pipe of $^1/_4$ in. nominal pipe size is usually sufficient. In extreme cases a pipe of $^3/_8$ in. size may be employed.

In order to start the operation it is usual to preheat the edge of the steel if a straight line cut is to be executed, or a localized region if a hole is to be pierced. For this purpose an oxy-acetylene torch with a large size welding tip is usually employed. The lancing operation is also sometimes started by drawing an arc between the lance and the work-piece. When the steel has been heated to a bright red, the end of the lance is brought against the heated area and with the operator at a safe distance and amply protected against flying particles of steel and slag, the oxygen lance valve is opened. Oxygen at pressure not over 75 or 100 psi. is then directed against the heated area of the steel. Sufficient heat is liberated by the combustion of the end of the lance (i.e., the iron pipe), which has been ignited by the preheated portion of the work-piece, to continue the propagation of the cut and to permit oxidation of the steel to be cut. Such oxidation might not otherwise be possible because of the greater heat-input requirement for cutting such steel. Rather than heating the work to start the lancing operation, it is the practice in some plants to heat the end of the lance by a torch or charcoal burner. Opening the oxygen lance valve slowly starts the burning at the end of the lance pipe. This is brought into contact with the surface to be lanced and, after burning

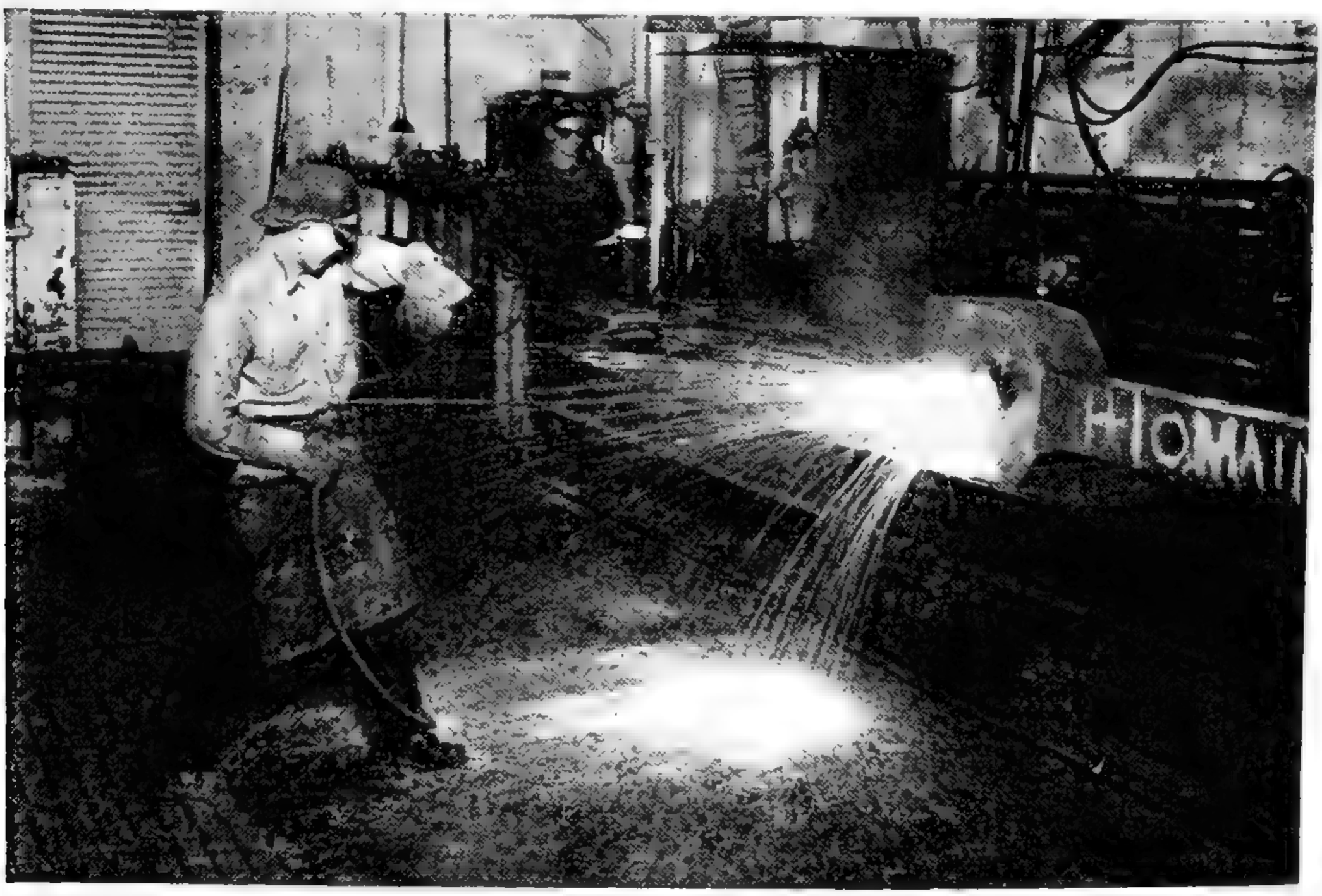

Fig. 12.—Lance Cutting

has extended to that surface, the oxygen valve is opened further to extend the reaction.

A non-consumable lance is sometimes used in heavy cutting operations to follow the cutting torch and supply oxygen lower in the kerf.

The end of the lance is so held in the cut or hole that the cutting-oxygen stream emerges in such a direction as to enlarge the cut or hole in the manner desired. The lance, of course, is slowly consumed during the operation, so that if the operation is greatly prolonged it is necessary to replace the lance pipe with a new length of pipe from time to time. Lancing operations are normally carried out in the horizontal plane to facilitate the flow of slag from the hole or kerf. It is also easier to handle the usual 20-ft. lengths of pipe in a horizontal position.

Accordingly, and in order that the cut is not lost during change of lances, replacement lances should be immediately available. In some instances it is desirable to use extra heavy steel pipe or pipe loaded with steel rods or wires or aluminum in the form of rods or shot in order to render the reaction more vigorous. Generally, however, the simple arrangement will be adequate.

The use of the lance is not confined to the cutting of steel. It has been successfully used for the piercing or cutting of nonferrous metals and even non-metals such as concrete vaults or foundations.

Scrapping

Scrapping is used extensively in demolition work where structural steel or obsolete machines or vessels are to be destroyed.

In general, no special equipment or techniques are required. A manual cutting torch is extensively employed for this work, while for very heavy sections the oxygen lance is used. In the demolition of very heavy ordnance material, manually manipulated, large machine-cutting torches have been successfully used. Since the main object of scrapping operations is to reduce the steel in a structure or machine to a convenient size for handling and disposition, careful manipulation to produce quality cuts is not essential. For scrapping work, speed of operation and convenience of handling are usually the main requisites.

Rivet Cutting

An oxygen-cutting torch with a tip designed for rivet cutting is often used in place of a chipping hammer for removing the heads of rivets which must then be punched out. Technique is of paramount importance, since it is essential that the head of the rivet be cut without damage to the plate itself. Rivet cutting technique is the result of care, diligence and practice and it must be learned by experience. Suffice it to say, that an experienced operator in rivet cutting can remove rivets rapidly without harming the plate or altering the original rivet hole.

Heavy Cutting

Heavy cutting, defined arbitrarily as the cutting of steel having a thickness greater than 12 in. and ranging upward of 48 in. or more, has been successfully accomplished in the past but usually with uncertain results. Recent studies of the fundamental factors involved have done much to clarify this phase of oxygen cutting and have resulted in putting these applications on a concrete, scientific and predictable basis. Heretofore, heavy cutting was considered more or less of an art to be practiced only by the initiated, with chances of success so problematical as to make it uneconomical.

Results of extensive technical studies under conditions that could be carefully controlled have shown that heavy cutting can be repetitively done with operating conditions properly interrelated, on this basis of fundamentals which are not particularly different from those applying to the cutting of ordinary thicknesses. However, the factors affecting cutting must be understood, and greater attention must be given to those signs visibly indicating correct or faulty cutting conditions.

One of the important points to realize is that contrary to generally accepted belief, high pressures are not required for heavy cutting. Nor is it necessarily true that with increased thickness of the section, the cutting-oxygen pressure must be very greatly increased. Analysis of test results obtained from many hundreds of heavy cuts has indicated that oxygen flow is the controlling factor, and that tip size and operating pressure are in-

volved only in so far as these values must be such as to provide the necessary flow required for the thickness being cut. Cutting-oxygen pressures, measured at the entry to the cutting orifices, of the order of 7 to 50 psi. have been found adequate for the heaviest cutting attempted (upward of 48 in.) provided the tip and equipment are correctly selected for the job. Realization that the pressure at the torch entry is the pressure of paramount importance in comparing results of different heavy cutting operations, is a necessary requisite to obtain the correct perspective in this work. In the past, measurements of pressures indicated at the regulator, or at some point removed from the torch, without regard to restrictions nearer the tip, have led to much of the confusion existing in previous operations and have resulted in failure to obtain comparable results at different times when the conditions were not exactly duplicated. By predicting performance on the basis of flow, rather than of pressure, heavy cutting data can be resolved along clearly defined lines.

may be used as a starting point in selecting the correct equipment and operating conditions, while the actual values for efficient operation on a particular job can only be obtained by trial and experimentation.

Recommendations as to the speed of travel are not included in Table 4, but speeds between 2 and 6 in. per min. are realized in the range of thicknesses covered. A speed of 3 in. per min. is possible for thicknesses up to at least 36 inches. The correct speed is obtained by observing the operating conditions carefully and making adjustments accordingly when the actual cutting is in progress.

Techniques for starting the cut differ from those used with thinner material. The start of the reaction is materially slower, but the reaction once started is more marked and spectacular. Sufficient time is required to permit the action to become stabilized. Figure 13 indicates some of the correct and incorrect starting conditions to be observed. Sketch *A* is the desirable starting position with

Table 4—Data for Heavy Cutting

Thickness of Steel, In.	Oxygen Flow, Cu. Ft./Hr.	Diameter of Cutting Orifice, In.	Cutting-Oxygen Pressure at Torch, Psi.
12	1000–1500	0.147–0.221	26–56
16	1500–2000	0.1935–0.290	25–49
20	1500–2500	0.200–0.221	25–48
24	1600–3000	0.221–0.332	22–48
28	2400–3500	0.230–0.400	18–44
32	2600–4250	0.250–0.450	16–40
36	3000–4600	0.290–0.500	12–38
40	3400–5000	0.330–0.550	10–33
44	3800–5500	0.375–0.550	9–29
48	4500–6000	0.422–0.600	7–27

In terms of flow it has been found possible to arrive at a rough demand constant which will be useful as a guide in selecting equipment suitable for a given job. Different sources give varying constants, but in terms of thickness measured in inches. these demand contants usually fall within a range of from 80 to 125 cu. ft. per hr. per inch of thickness (80T to 125T, where T is in inches of thickness). Table 4 gives the range of operating conditions that cover normal heavy-cutting operations. In using these data it must be clearly understood that the data obtained from the table may not be entirely suitable for all heavy cutting operations, although these values have been used successfully. It

the molten zone extending down the face of the material rather than on the top. Sketches *B*, *C*, *D*, *E* and *F* are the result of incorrect procedure, and are self-explanatory.

With ideal finishing conditions, it is possible to achieve drop cuts without recourse to special techniques. Figure 14 illustrates finishing conditions for heavy operations, with the desirable situation for producing a drop cut depicted at *A*.

In general, the necessary conditions for successful heavy cutting on a production basis are: (1) an adequate gas supply on hand, sufficient for the job; (2) equipment of sufficient size, both structurally to handle the heavy loads imposed and of sufficient capacity to handle the range of

speeds and gas flows necessary; (3) and, most important, skilled personnel trained in the proper techniques for heavy cutting.

The first item is important to insure completion of the job without interruption due to having insufficient gas capacity available. Not only must the gas source be adequate, but the pipe lines and station drops and regulation equipment must be of a size suitable for the gas flows to be handled. Reference to Table 4 will indicate that the gas flows for heavy cutting are extremely large and the maximum momentary loads are likely to be even heavier. All unnecessary restrictions in the gas supply lines should be carefully avoided.

altered during the cutting operation to compensate for changing conditions.

Torches must be constructed with a minimum of internal restrictions to the gas flow. For cutting materials up to about 20-in. thick, torches having the valves attached are usually satisfactory, but for heavier work valveless torches should be used. These permit the location of large valves away from the heat of the cutting operation. Torch gas capacity for very heavy cutting should be in the neighborhood of 5000 cu. ft. per hr. for cutting oxygen and 300 cu. ft. per hr. each for preheat oxygen and acetylene.

Tips are also an important considera-

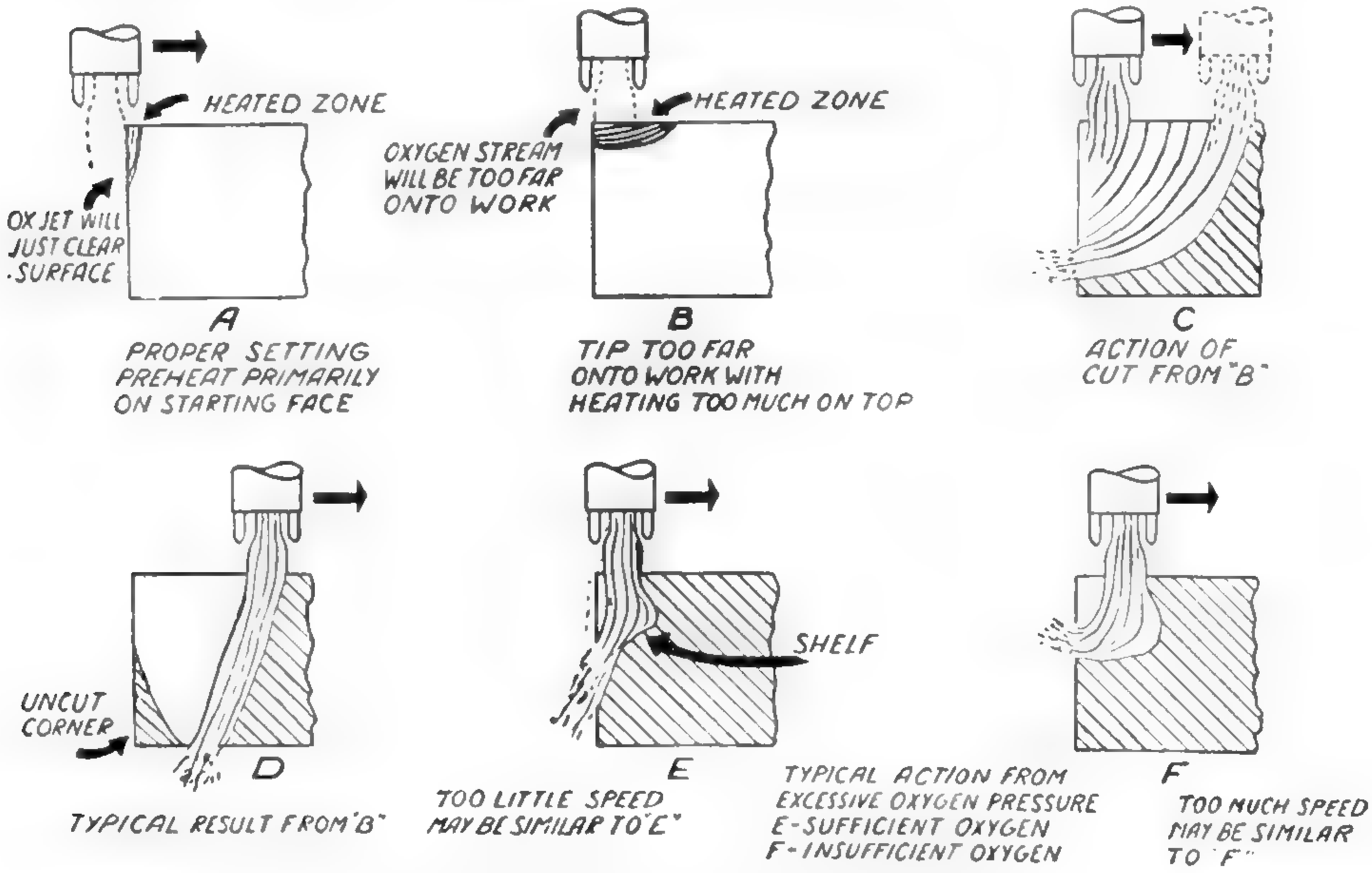

Fig. 13.—Starting Conditions for Heavy Cutting

The cutting equipment and machines also must be selected for the particular job under consideration. The machines used to carry the cutting torches must be sufficiently massive and of wide gage to carry the heavy loads of the cutting torches and the supply hoses, and should be properly counterbalanced where necessary. These precautions are essential for safety of the operating personnel. The machines must be capable of maintaining a uniform speed, and be geared to provide a minimum constant speed down to 1 in. per min. or less. They must also be readily adjustable so the speed can be

tion. The correct design of the preheat flames for heavy cutting is essential for success. Preheat flames must be relatively large, otherwise complete penetration of the cut will not be obtained and excessive drag will be observed.

One of the major items for successful heavy cutting is trained personnel, who are thoroughly familiar with the equipment and its control and who have no hesitancy about attempting heavy-cutting operations. The operators should be trained to be painstaking and exact in their work, and to make accurate setups, and alignments. A misalignment of a

fraction of an inch, which would be of no consequence in ordinary cutting, can become so exaggerated when dealing with sections 48 in. in thickness that an expensive piece of steel may be ruined. saws and slicers and without disturbing the mill cycle. Such location for the cutting-oxygen apparatus is particularly advantageous when dealing with high-carbon or alloy steels which from metal-

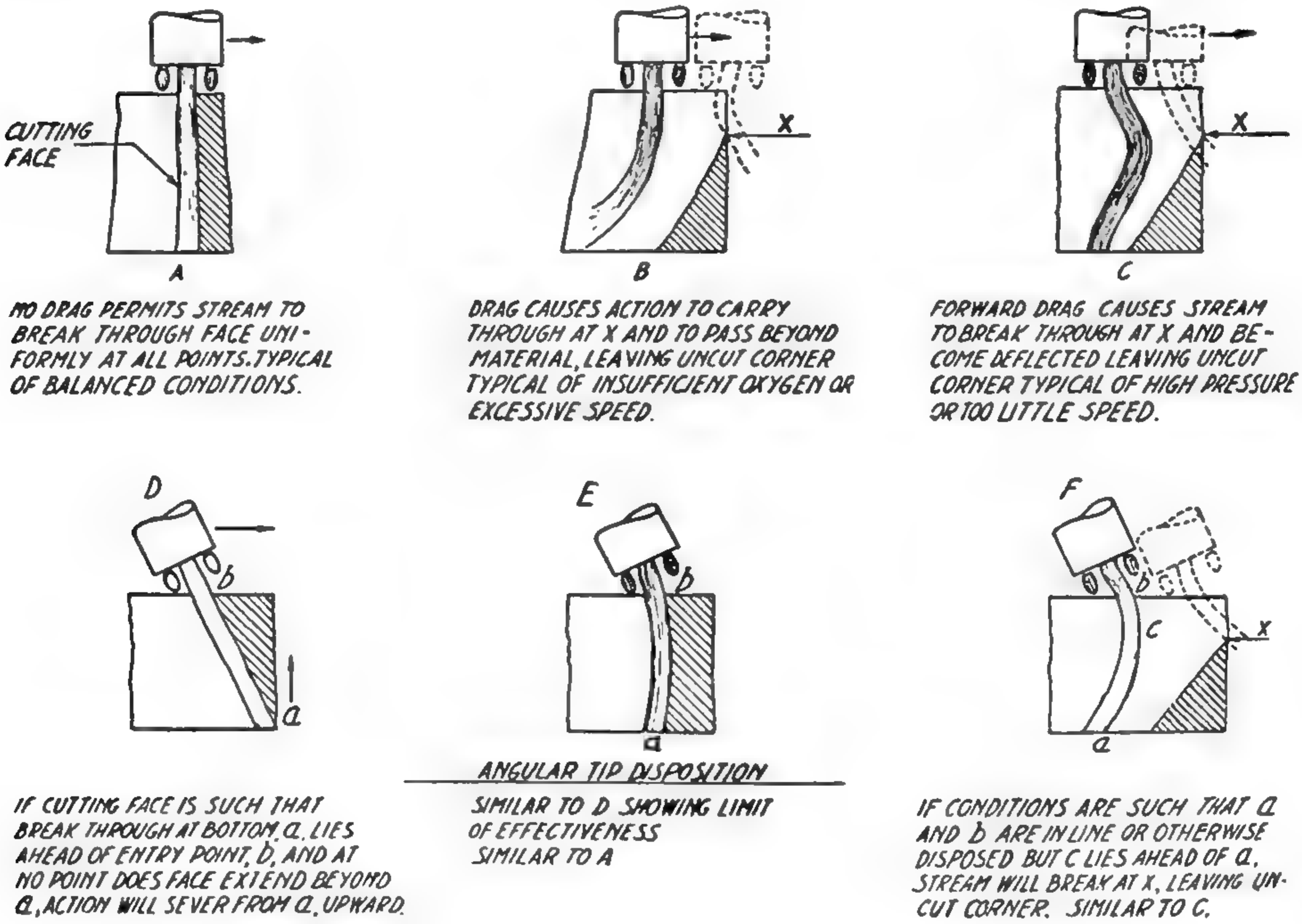

Fig. 14.—Finishing Conditions for Heavy Cutting

The well-trained operator will be able to initiate a cut with full realization of the problems to be encountered and be alert to make immediate adjustments to compensate for altering conditions. Because normal cutting hazards are greatly magnified in heavy cutting, the operator should wear proper clothing and protective devices.

Cutting at Elevated Temperatures

Unprecedented demands for greater production, mainly in the steel industry, have led in recent years to the utilization of oxygen cutting for severing steels at elevated temperatures. These temperatures, about 1500 to 2000° F., are considerably higher than preheating temperatures necessary for cutting high-carbon steels. Hot cutting is used to good advantage directly in the rolling line, where the high speeds inherent in the process permit its use in place of shears, lurgical considerations would normally require preheating before cutting. Its use increases production, and can effect measurable economies.

High-speed cutting at elevated temperatures requires gas flows considerably greater than those used for cold cutting of materials of equivalent thickness. Cutting equipment (machines, torches and regulators) are required of sufficient size to handle the flows normally required for hot cutting. The gas supply must be unimpeded, and large supply lines and large hoses without unnecessary restrictions between the regulatory point and the torches should be specified. Care should be taken to assure that the gas supply is adequate, and that peak loads on the piping system at some other point will not influence the supply to the cutting location. Torches, as in the case of those used for heavy cutting, should be selected with due consideration to

their capacity and to the absence of restricting elements to the flow of gas which if present may be a source of turbulence. All equipment including the torch and its suspension are required to be water cooled. When laying out a hot cutting operation, proper attention should be directed toward providing adequate safeguards to protect the operating personnel from the intense heat and to guard against injury from flying slag and scale.

Oxygen cutting at elevated temperatures follows the same general principles that apply to cold cutting, and tolerances and quality of cut can be obtained in a similar degree as in cold cutting, provided the highest speeds are not required. With a sacrifice in quality, severance drop cuts* may be obtained at high speeds. However, careful study of a particular problem is required to arrive at an economical cutting speed in relation to the gas flows involved. The economical speed is not necessarily the maximum cutting speed obtainable. The increase in speed to the maximum possible does not at all times compensate for the increased cost for the gas flows that are necessary. Before contemplating a hot cutting operation on a production basis, studies of the economic factors should be made and the reader is referred to the technical literature on this subject listed in the bibliography at the end of this Chapter.

While a complete discussion of hot cutting is beyond the scope of this chapter, some of the factors and possibilities of the process are summarized in the following paragraphs.

For hot-cutting work, tips of both the divergent cutting-oxygen orifice type and the standard, straight drilled orifice type are used. To increase speed by increasing the gas flow, it has been found from fundamental studies of the subject that it is preferable to use a tip with a larger orifice rather than to increase the oxygen operating pressure. For any given tip there exists an optimum flow rate giving the maximum speed; any larger flow caused by increased pressure with the same tip leads to a definite loss of speed.

In hot cutting, two distinct types of cutting are possible—quality cutting and severance cutting. Quality cuts at elevated temperatures can be made which are the equivalent in finish and dimensional tolerance of quality cuts on cold material of the same thickness, but at faster cutting speeds. Figure 15 shows this difference between cutting speeds for quality cuts on cold material and similar cuts on the same material made at one particular elevated temperature.

For severance cuts at elevated temperatures much larger increases in speed are realized (at the expense of the quality of the cut) over those obtained on cold material. For many applications, quality is not of major importance, and the advantages to be gained by increased cutting speed make severance cutting at elevated temperatures advantageous.

Ratios of oxygen to acetylene of 15 or 18 to 1 are best for producing quality cuts; ratios of 20 or 25 to 1 are best for severance cuts. (The oxygen in both these cases includes both cutting and preheat oxygen.) However, economic considerations will be a deciding factor in selecting the optimum oxygen-acetylene ratio. Other factors to be considered more in hot cutting than in cutting at room temperatures are torch angularity, and height from tip to work. Certain studies on 6-in. material indicate that, with torch tip inclined forward in the direction of travel about 2 deg. from the perpendicular, maximum cutting speed is obtained. A distance of approximately $1^1/_4$ to 2 in. from the steel to the tip gives best results. Such a distance minimizes disturbances caused by fouling of the tip by slag or scale, and at the same time reduces melt-down of the upper edge of the kerf.

Both standing starts and running starts are possible with the hot-cutting process. Standing starts are commenced immediately after the tip has been positioned and the cutting oxygen is turned on. The few seconds required to position the tip are ample for preheating. Care must be taken, however, to position the tip so that the cutting-oxygen jet at the start does not impinge on the surface over one quarter its diameter. Otherwise, fouling of the tip and the formation of a shelf partway down the face of the cut are likely to occur.

Running starts can be accomplished at speeds below those used for standing

* A severance cut, as opposed to a quality cut, is one in which the cut surfaces are no longer plane and parallel.

starts. However, additional heat in the form of auxiliary preheat or by introducing iron powder through the tip, may be required to accomplish these results, depending to some extent on the shape factor and on the temperature of the material.

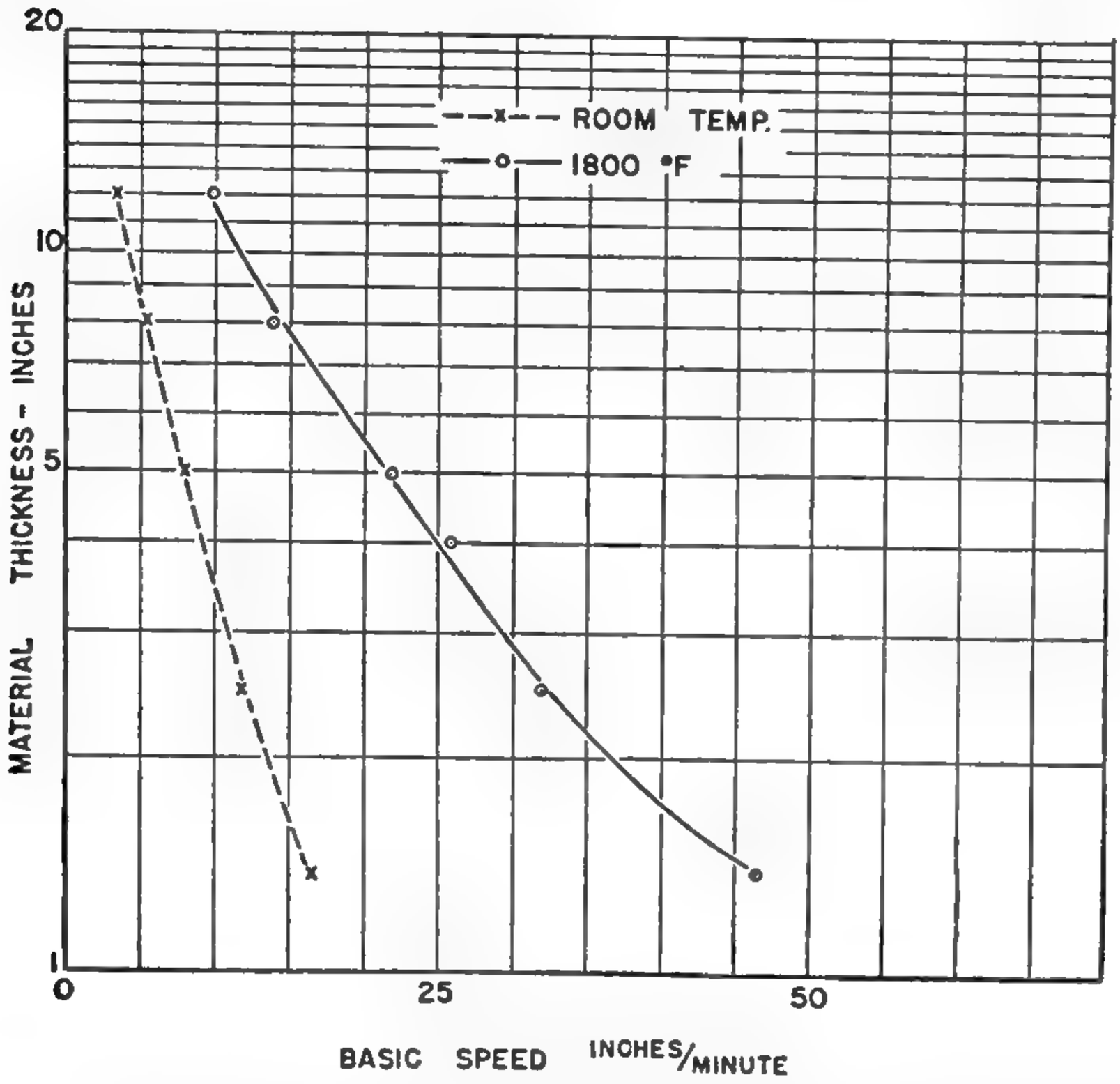

Fig. 15.—Cutting Speed as a Function of Thickness for Basic Cutting Tip; Square-Corner, High - Quality Drop Cuts and Standing Starts

(SAE 1020; Room and 1800°F. Cutting Temperatures)

The temperature at which hot cutting is done affects the speed of the operation and is associated with troubles that may be encountered. Research in this phase of the subject presently indicates that shelving and other difficulties are more pronounced at temperatures below about 1700° F. Above the upper critical point of a specific material, difficulties are minimized. The effect of temperature on cutting speed is shown in Figs. 16 and 17.

Carbon content of the material has a marked effect on cutting speeds. Maximum speeds for both quality and severance cuts are obtainable in steels containing about 0.75% carbon. Speeds decrease markedly with any variation of this particular carbon content. Effects of alloying elements are not considered in this discussion.

Metallurgically, hot cutting results in a cut surface free of carbon enrichment, and with a scarcely perceptible hardness gradient. The cut edge shows evidence of a slight decarburization, mainly in the areas immediately under the preheat flames. Micrographs show that grain growth along the cut surface is not appreciable. Hot cutting with correct procedure results in a perfectly sound material with a normal structure with no indication of thermal checking or other undesirable features.

Surface scale of appreciable thickness will necessitate operation at lower speeds and may require additional preheat to effect the cut. The presence of tightly adhering surface scale not only influences the cutting speed, but also may result in shelving and excessive drag, which in severe cases may result in leaving the starting corner uncut.

Kerf widths obtained for quality cuts at elevated temperatures can be practically identical with those for cold cutting, provided proper cutting tips are used. Quality cuts at elevated temperatures can be made with preheat controlled to a degree such that melt-down of the upper edge is no more pronounced than in cold cutting. Severance cutting at elevated temperatures on the other hand results in a noticeable melt-down.

However, for severance cuts this factor is usually negligible. At the temperatures employed in hot cutting, the tenacity of slag and scale is strongly marked.

Cutting of Materials of Poor Cutability

In the discussion of the effects of alloying elements on the cuttability of various materials, it was noted that certain alloys develop high resistance to the action of the cutting-oxygen stream, making it difficult or sometimes impossible to propagate the cut without resort to special techniques. One such technique for improving the cutting action on an alloy steel difficult to cut by the usual procedure is to clamp a mild steel *waster plate* tightly to the upper surface, and to make the cut through both thicknesses. By such means there will be noticeable improvements in the cutting action, as the molten mild steel has the effect of diluting or reducing the percentage of alloying content.

However, to overcome the obvious objections to the practice of employing waster plates, and to extend the use of oxygen cutting to materials not susceptible to such techniques, attention has been directed in recent years to the development of equipment for more efficient use on materials of poor cuttability. The strides that have been made have been noteworthy and it is now possible to cut many of the alloy steels which heretofore could only be cut by a *melting action* rather than by a true oxidation of the metal. One of the principal alloy groups to which the oxygen-cutting process has thus been extended is the chromium irons and stainless steels.

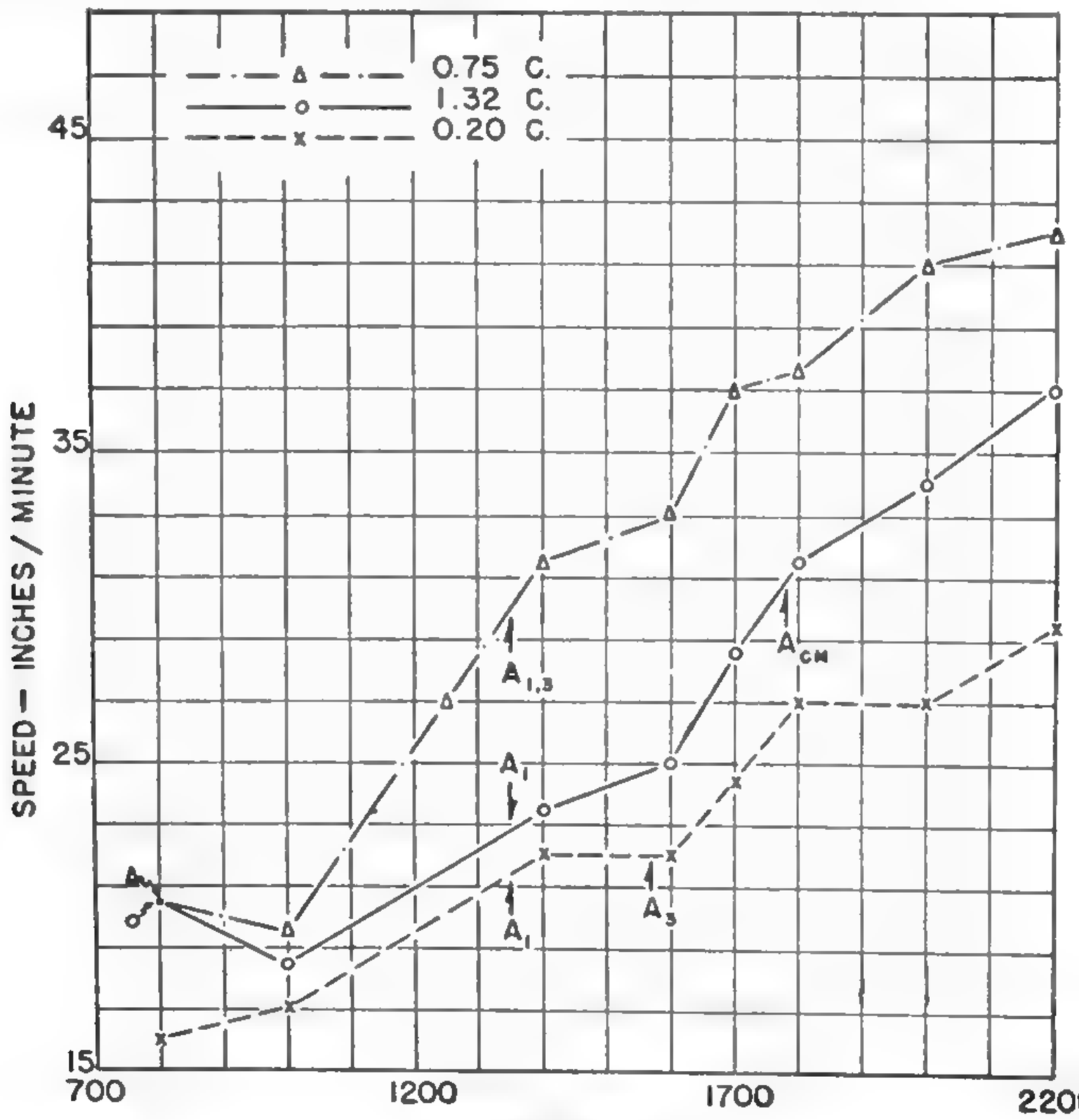

Fig. 16.—Cutting Speed as a Function of Temperature for High-Quality Drop Cuts

For cutting these materials, it has been found necessary to introduce a powder or flux along with the cutting-oxygen stream in order to remove the oxides of the alloying elements which prevent the oxygen stream from reaching the iron and allowing the cutting action to proceed. The high temperatures resulting from the use of an electric arc have also been combined with the use of oxygen to cut materials of poor cuttability. This

oxygen-arc process is further explained in Chapter 25.

There are two methods for accomplishing the cutting of these materials, both of which are similar in the respect that a powder or flux is directed into the cutting area. In one process finely divided iron powder is used, being directed into the cutting stream through orifices adjacent to the regular cutting-oxygen jet of the tip. The second process makes use of a nonmetallic powdered flux which is introduced into the cutting-oxygen stream and is thus introduced to the cutting zone.

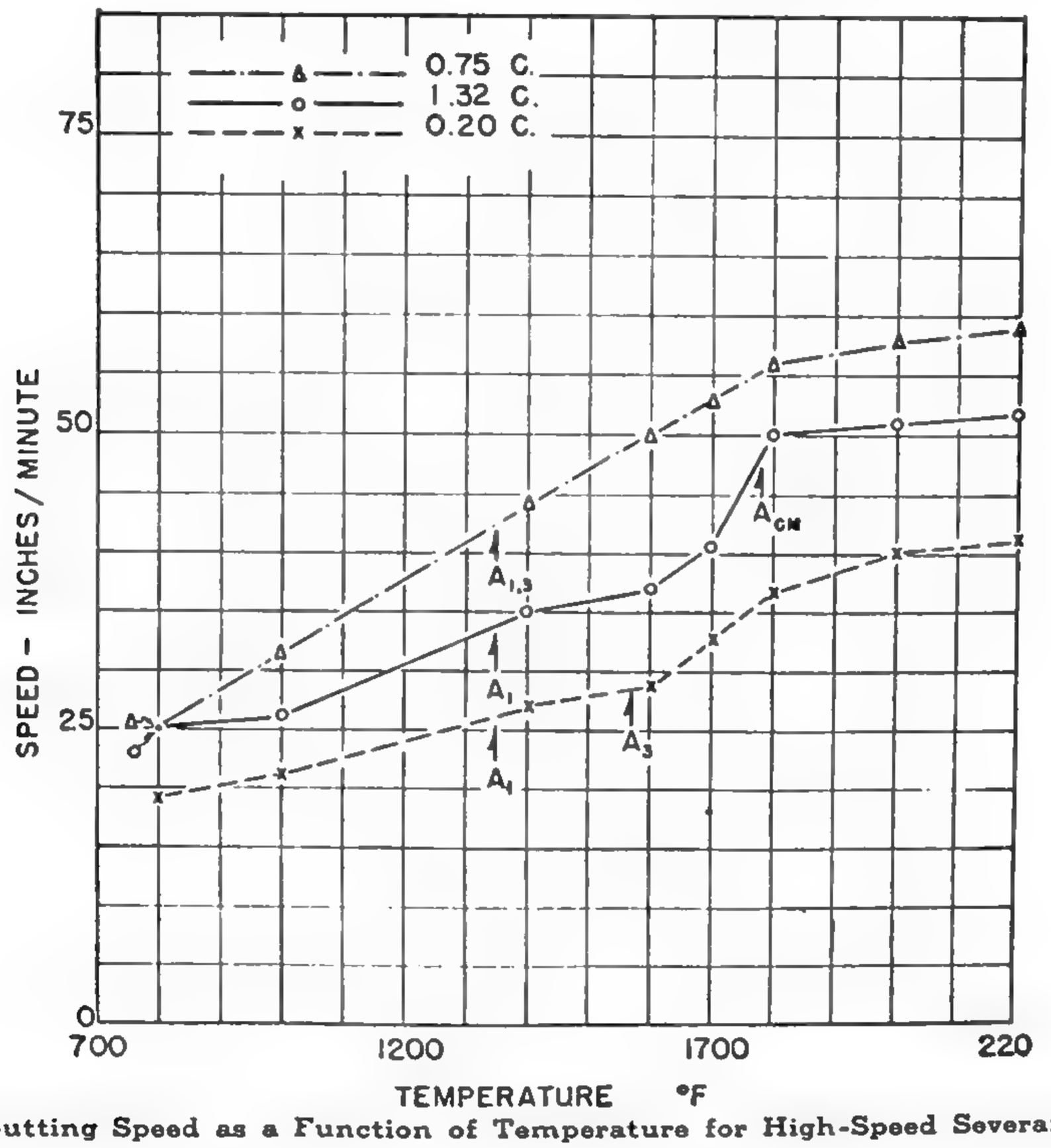

Fig. 17.—Cutting Speed as a Function of Temperature for High-Speed Severance Drops

In the former method using iron powder, it is believed that the cutting action is accelerated by the fact that the iron powder introduced into the cutting area is readily oxidized liberating a large quantity of heat. This additional heat raises the temperature at the cutting face high enough to melt the refractory oxides which protect the steel from the action of the cutting oxygen. The refractory oxides in molten form can then be flushed from the cutting face and the cutting oxygen therefore can act directly upon the remaining iron in the steel. It is also thought that the iron oxide particles liberated in the burning of the iron powder create a fluxing action on the chromium component of stainless steels. The iron-powder method is used successfully on the chromium irons and stainless steels, and has been used with success on cast iron, copper, bronze and various alloys with small ferrous content.

The second method, known as flux-injection cutting, operates on a different principle. In this process, a nonmetallic compound is brought into contact with the refractory oxides. The action can be thought to be of the nature of *fluxing* in which the nonmetallic compound unites chemically with the refractory oxides at the face of the cut, producing a slag of lower melting temperature which is washed and eroded out of the cut exposing the steel to the action of the cutting oxygen. Both methods have proved very successful for use in cutting chromium irons and stainless steels.

Auxiliary equipment is essential to dis-

pense the fluxing material (flux or iron powder). A pressurized hopper is employed to store the fluxing material and to introduce it uniformly and in the required quantities. An injector or a magnetic vibrator installed as a part of the flux hopper meters the correct amount of the fluxing material. From the hopper it is carried along, either with the oxygen stream, or separately through an additional hose line, in this case being entrained with a separate gas stream.

The techniques used for flux-injection and powder cutting are essentially similar to those used for oxygen cutting of mild steel. The speed of cutting is similar to that used for a comparable thickness of mild steel. Success of the operation depends on the proper adjustment of the flux or iron powder flow in relation to the thickness of the material being cut, and likewise on the analysis of the material. It is therefore difficult to give generalized operating data, and it is suggested that recommendations of the manufacturers of the equipment be followed. However, any recommended adjustments of the pressure and flux or iron powder flow should only be used as preliminary settings, and the actual settings to be employed should be obtained by making trial cuts on the specific material under consideration.

Cast iron is classified as a material difficult to cut. While the iron-powder cutting process described above may be used with excellent results on cast iron, it is possible by employing the older techniques to cut cast iron with the ordinary cutting torch.

The difficulty in cutting cast iron is brought about by the presence of relatively high percentages of graphitic carbon, which by virtue of its free condition offers some protection for the iron against oxidation, and which by reason of the large amounts present in cast iron will result in an appreciable CO_2 pollution of the cutting-oxygen stream, reducing its reactivity before it reaches the iron itself (see section on Oxygen Purity). Moreover, the fact that the melting point of cast iron is less than that of the iron oxide means that the iron will tend to melt rather than to oxidize. It should be observed that in oxygen cutting of steel the melting point of the steel is higher than that of the oxide so that the steel beyond the immediate region of oxidation maintains its rigidity, and the oxide in a fluid condition is readily washed out of the cut by means of the cutting stream. In this manner a minimum quantity of iron must be removed, and there is a maximum opportunity for a relatively unpolluted oxygen stream to attack fresh regions. With cast-iron cutting this fortunate relationship is not realized.

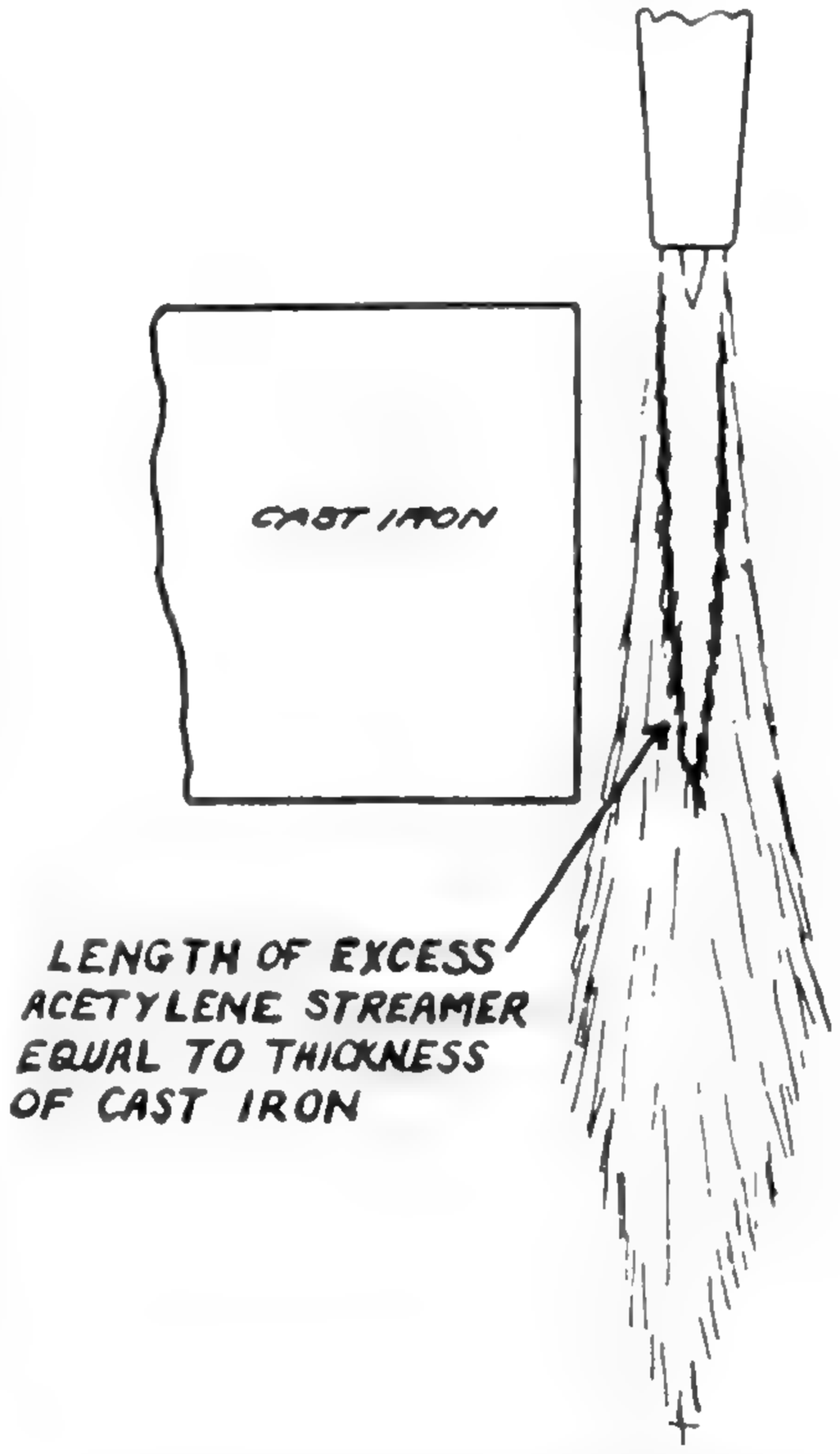

Fig. 18.—Flame Adjustment for Cutting Cast Iron

In view of these conditions it should be obvious that to cut cast iron successfully the operation must, to an extent, be thought of as a melting operation in which the oxygen jet may be more valuable as a physical eroding and washing agent than as a chemically active agent. Accordingly, in actual practice with regular equipment the preheat for cast-iron cutting must be intense. Moreover, it is necessary that much heat be liberated deep in the cut. The former is effected by using larger and more numerous preheat orifices for cast-iron cutting than for more normal cutting operations.

The latter is effected by adjusting the preheating flames so that combustion is completed in the lower levels of the cut. That is, a considerable excess of acetylene is permitted in the preheating flames, as illustrated in Fig. 18, and this excess of acetylene unites with some of the oxygen of the cutting jet in the lower levels of the cut.

If the oxygen jet is moved forward continuously as in the ordinary cutting operations, the jet itself will prevent the heat, liberated in the lower regions of the cut as just described, from being effective at the forward or active edge of the cut. Consequently, movements such as those illustrated by Fig. 19 are neces-

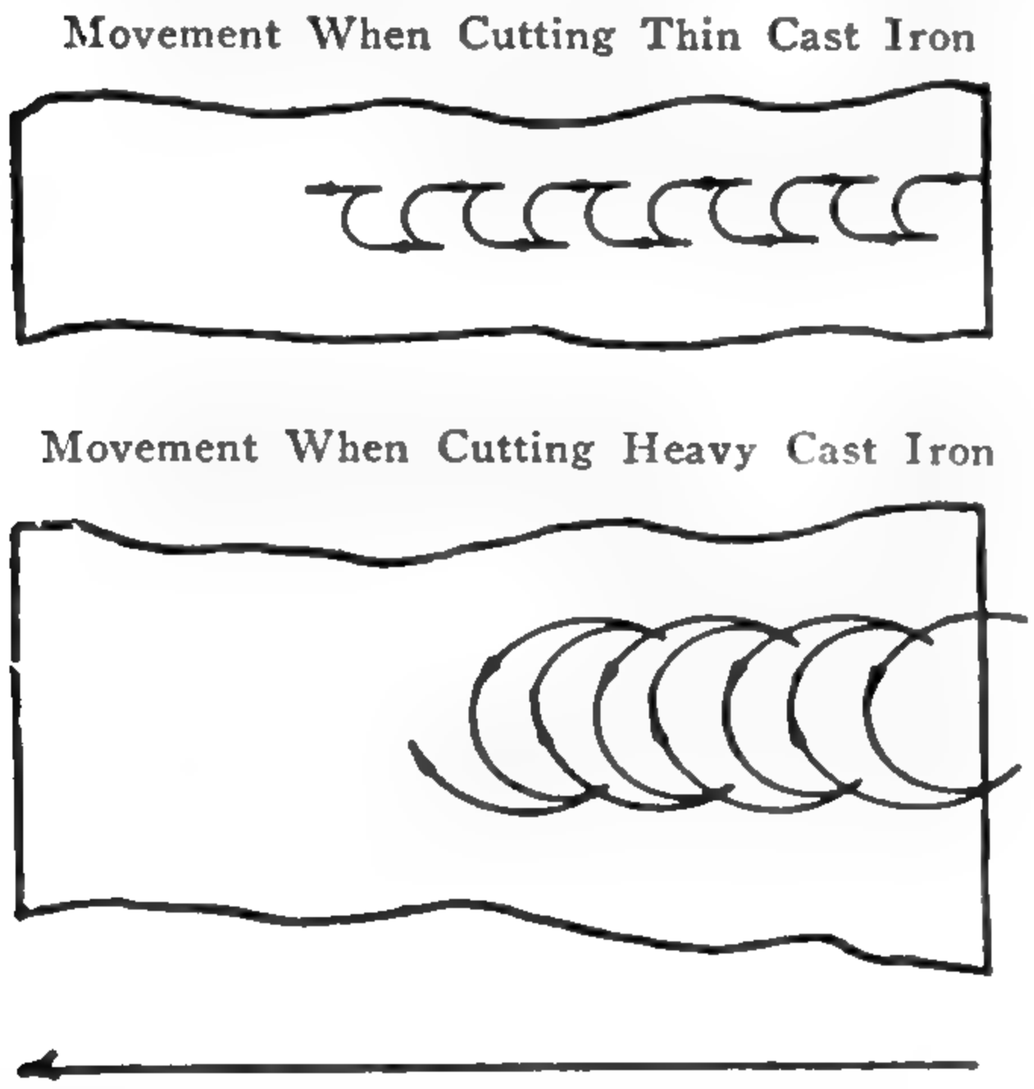

Fig. 19.—Manipulation of Cutting Torch and Tip for Cutting Cast Iron

sary in order that the intermediate and lower portions of the cut may be maintained at the proper temperature, and in order also that the cut may be wide enough to prevent any possibility of the molten iron freezing in the lower levels.

Underwater Cutting

Repairing damage to piers and dry docks and cutting away damaged plates of ships below the water line requires a tool which can be used with facility by divers working in considerable depths of water.

Underwater cutting should only be attempted by those fully qualified and competent in underwater work. The problem is not only that of severing steel under water, but it also involves correct handling of all the diving gear, and thus is not to be attempted by anyone except those fully conversant with this difficult and hazardous work.

The technique for underwater cutting is not materially different from that used in cutting steel in the open air, for the torch embodies the same features as a standard cutting torch. In the underwater-cutting torch, fuel gas and oxygen are mixed together and are burned to produce the preheat flame, and a cutting-oxygen jet is provided to supply the oxygen to cut the steel. However, an additional feature is required of the underwater-cutting torch, in that provision to maintain an *air bubble* surrounding the cutting tip is needed. The air bubble is maintained by delivering compressed air to the torch, and this compressed air is ejected around the tip, sheathing it in a bubble of air, or an artificially created atmosphere, in which the tip can function normally. Actually, the air shield is not necessary to keep the torch lit under water. All the elements necessary for combustion, fuel gas and oxygen, are delivered to the tip, and although the gas ratios are different from those used in air, the tip would function under water if the air bubble were not present. The air shield does, however, serve the purpose of stabilizing the flame, and at the same time displaces the water from the cutting area permitting more efficient heating of the steel, since water is a far better conductor of heat than is air.

The underwater-cutting torch is furnished with connections for three hoses to convey compressed air, fuel gas and oxygen. In addition, for controlling the air bubble and maintaining it in the required position at the end of the cutting tip, a metal shield is attached at the end of the torch. The shield serves in a dual capacity. It controls the formation of the air bubble and also is made adjustable so that the tip can be held at the correct distance from the work. This second feature is essential for underwater work where the torch is employed under adverse lighting conditions and in cumbersome diving suits that would preclude any possibility of use of a torch without means for mechanically holding the torch at the optimum separation from the steel. Generally, slots in the shield are provided to allow the burned gases

to escape to the surface. A short torch is used to reduce the *kick* accompanying the release of the gas jet against the surrounding water.

Since underwater cutting is performed at varying depths, gas pressures must be greater than those used in cutting under atmospheric conditions and must be adjusted according to the depth at which the work is being performed. At a depth of only about 35 ft., water pressure equals 15 psi. Acetylene should not be used at pressures over 15 psi. Hydrogen is, therefore, almost universally used for underwater work, because it can be compressed without danger, although the lower flame temperature of the oxy-hydrogen flame is undesirable. Propane can be used in warm waters.

Table 5—Underwater Cutting Pressures

Depth, Ft.	Water Pressure, Psi.	Compressed Air, Psi.	Hydrogen, Psi.	Oxygen, Psi.
10	4.3	35–60	20–60	80
20	8.6	40–65	25–65	85
30	12.9	50–70	35–70	90
40	17.3	55–80	40–80	100
50	21.6	60–85	45–85	105
60	25.9	70–90	55–90	110
70	30.3	75–100	60–100	115
80	34.6	85–105	70–105	120
90	38.9	90–110	75–110	125
100	43.3	95–115	80–115	135
125	54.1	115–125	100–125	145
150	64.9	130–140	110–140	160
175	75.7	145–155	120–155	175
200	86.6	165–170	135–170	190
225	97.4	180–185	150–185	200

Representative figures for gas pressures used in underwater cutting are given in Table 5. As in all tables indicating recommended pressures, these figures must be regarded as approximate only, and should only be used as a starting point for correct pressure adjustment under the conditions of the particular job. Air pressure will in general be adjusted to a value slightly less than that of the oxygen pressure to avoid interference with the cutting jet.

Materials Which Can Be Cut

The section on the Effects of Alloying Elements should be referred to in conjunction with this discussion. While it is obviously impossible to cover the vast number of steels commercially available to indicate the relative ease with which they may be cut, the following discussion should offer an indication of the results to be obtained. Before commencing any cutting operation it is advisable to know the analysis of the material in order to evaluate to some degree the probable success of the operation and to determine whether special equipment or techniques may be necessary.

Carbon and Low-Alloy Steels.—Low carbon and mild steels (carbon content ranging up to about 0.25% C) are cut without any difficulty, and no special precautions need be observed. This category includes the majority of structural steels, such as the steels used in building construction, shipbuilding, bridges and similar engineering projects.

Steels with a carbon content higher than 0.25% C and alloy steels, are susceptible to hardening, the hardenability increasing as the carbon or alloy content increases. Since the action of the cutting torch is essentially similar to a flame-hardening procedure with the metal at and near the cut being raised above its critical temperature and with the mass of metal adjacent to the cutting area serving as a quenching medium, hardening will result at the faces of the cut unless special precautions are observed. In severe cases the hardening will also be accompanied by cracking resulting from the stresses set up during cooling. However, by preheating the metal before commencing the cutting operations these difficulties can be minimized or overcome entirely.

In general, plain carbon steels and low-alloy steels may be cut without undue difficulty.

Stainless Steels.—Steels containing less than 5% chromium may be cut without too great difficulty provided the surface of the metal is clean. However, when the chromium content is increased beyond this value, flux injection or iron-

powder cutting is required to obtain acceptable results. These methods can be used to cut the chromium irons and steels as well as the stainless steels usually encountered in industry. However, as the chromium and nickel content of the alloy increases, it becomes more difficult to make quality cuts. The stainless alloys, 18–8 (AISI Type 304) up through 25–20 (AISI Type 310) may all be cut by the iron-powder process, although much greater care is necessary to produce good cuts in the 25–20 material. Materials such as 35–15 may be cut with difficulty under carefully controlled conditions.

Materials of Poor Cuttability.—Cast iron because of its graphitic nature is difficult to cut under ordinary operating procedure. However, by using special techniques, as described previously, it is possible to effect an acceptable cut. It is also possible to use iron-powder cutting with excellent results on cast iron.

High manganese alloys (containing up to 14% Mn) are cut only with difficulty, and must be preheated for best results.

The nonferrous alloys present special problems in cutting. Since they do not oxidize readily, the primary action of the cutting-oxygen stream cannot be utilized. The limited cutting action which is possible when using a cutting torch on very light sections of nonferrous alloys is not a true oxidizing action, but rather a melting and eroding action is responsible for the severing of the metal. The iron-powder method is used successfully to cut many of these materials.

Fields of Application

Oxygen cutting has become an accepted tool in practically all the major construction industries using steel as the basic material. The facility with which it can be adapted economically to the cutting of steel of various thicknesses, and of intricate shapes, has resulted in its competing favorably with machine tools. In fact, oxygen cutting has supplemented many machine tools, or to a large degree supplanted them. It is used in many instances to remove excess metal quickly, reducing finishing operations to a minimum. Again in other cases, the cut made is of such precision that it is acceptable without any additional machining.

In the same manner that welded fabrication has been substituted for more costly methods of construction, so oxygen cutting has provided a better, more economical and practical means for cutting parts and shapes to be fabricated from steel. Only a minimum inventory of steel plate and shapes is necessary to permit the production of a diversity of products. The advantages that lie in this fact alone make oxygen cutting desirable and profitable.

In the construction field, welded design often requires that large structural shapes be fabricated by welding. The preparation of these shapes can be materially aided by oxygen cutting.

Steel mills make extensive use of oxygen cutting in all stages of mill production. Special machines are used for cropping billets and hot cutting the blanks and unfinished rolled sections.

Other machines are employed to cut finished beam sections to size and to trim off the cropped ends. In the warehouse, oxygen cutting may be used to good advantage to cut steel shapes to the customer's specifications.

Shipyards find wide use for oxygen cutting in preparing plate for welding, or for removing damaged steel for replacement in the case of repair work. Steel plate is not only cut to size by the process, but also where welded construction is used, the plate is beveled by the oxy-acetylene torch.

Railroads in their repair shops and maintenance departments are large users of oxygen cutting. They make use of it also in their locomotive and car shops, and it is indispensable to their wrecking crews for clearing the right of way in case of a wreck.

To the salvage and scrapping industries oxygen cutting is an essential tool, permitting great savings in time and effort. It is being used to demolish obsolete structures, ships and equipment, reducing the steel to scrap which can be readily shipped back to the steel mills and used as raw material for future steel production. Many salvage operations, and especially underwater work, can only be accomplished with the use of oxygen cutting to remove debris and damaged sections, allowing repair work to be undertaken.

The usefulness of oxygen cutting as a tool for emergency work has long been

recognized. Police and fire departments make good use of this process in rescue work, and, in general, emergency and safety crews connected with utilities and transportation services are equipped with cutting apparatus to enable them to effect quick removal of steel. The portability of oxygen-cutting equipment, and the fact that the cutting outfit and cylinders are a self-contained unit not requiring connection to any utility facilities make oxygen cutting extremely useful for this service.

BIBLIOGRAPHY

1. *Importance of Impurities in Oxygen When Cutting Iron and Steel,* A. E. Tucker, Journal of the Soc. of Chem. Ind., July 15, 1911.

2. *Investigation of Oxy-acetylene Welding and Cutting Blowpipes,* R. S. Johnston, Technologic Paper No. 200, 1921, U.S. Bureau of Standards.

3. *Economics Through the Use of High Purity Oxygen in Cutting,* J. J. Crowe and G. L. Walker, The Welding Journal, March 1925.

4. *What Occurs During Oxy-Acetylene Cutting of Steel,* S. W. Miller, Acetylene Journal, November 1925.

5. *Oxy-Acetylene Cutting,* E. E. Thum, Iron Age, May 14, 1925.

6. *Oxy-Acetylene for Cutting Structural Steel,* D. E. Roberts, The Welding Journal, November 1928.

7. *Effect of Tip Sizes and Pressures Upon the Economy of Cutting,* J. J. Crowe and G. M. Deming, Proceedings of the International Acetylene Association, 1929.

8. *Cutting Steel Shapes with Oxy-Acetylene Torch Machines,* F. E. Rogers, The Welding Journal, February 1930.

9. *Some Methods and Effects of Machine Gas Cutting,* L. M. Curtiss, The Welding Journal, January 1932.

10. *Flame Cutting of Low Carbon Steel,* J. R. Dawson, The Welding Journal, June 1932.

11. *Machining with Oxy-Acetylene,* H. H. Moss, American Machinist, December 31, 1932 and January 4, 1933.

12. *Conditioning, Shaping and Machining of Carbon Steel by Oxygen,* H. H. Moss, The Welding Journal, January 1933.

13. *Machine Cutting and Flame Machining by the Oxy-Acetylene Process,* R. F. Helmkamp, The Welding Journal, February 1934.

14. *Oxy-Acetylene Cutting of Structural Steel,* H. H. Moss, The Welding Journal, June 1934.

15. *Hydrocarbon Fuel Gases for Cutting,* G. V. Slottman, Proceedings of the International Acetylene Association, 1935.

16. *Studies of Oxy-Acetylene Cut Steel Plate,* J. H. Zimmerman, Proceedings of the International Acetylene Association, 1934 and 1935.

17. *Flame Cutting,* A. Ussher, The Welding Engineer, November 1935.

18. *Cutting Structural Steel,* J. H. Zimmerman, Mechanical Engineering, 1935.

19. *Oxy-Acetylene Cutting* (Reference Manual), International Acetylene Association, 1937.

20. *Management of Machine Cutting Operations,* R. F. Helmkamp, Proceedings of the International Acetylene Association, 1937.

21. *How to Cut Stainless-Clad and Nickel-Clad Steel Plate,* H. V. Inskeep, The Welding Journal, August 1937.

22. *Cutting and Tempering of Structural Steels,* H. H. Moss, Proceedings of the International Acetylene Association, 1937.

23. *Structural Steel "Flame Softened" During Gas Cutting,* H. H. Moss, Iron Age, December 30, 1937 and January 20, 1938.

24. *Oxygen Cutting of Steel—Part I: Mechanical Properties and Metallurgy,* W. Spraragen and G. E. Claussen, The Welding Journal Res. Suppl., July 1939.

25. *Plate Edge Preparation for Welding,* H. E. Rockefeller, The Welding Journal, January 1940.

26. *Oxygen Cutting of Steel—Part II: Oxygen Cutting Procedure,* W. Spraragen and G. E. Claussen, The Welding Journal Res. Suppl., May 1940.

27. *Flame Machining—Control and Applications,* G. L. Walker and W. G. Sylvester, The Welding Journal, February 1941.

28. *Survey of Welding and Cutting in Ship Construction,* F. G. Outcault and J. M. Keir, The Welding Journal, January 1942.

29. *Billet Cutting for Steel Forgings,* H. E. Rockefeller, The Welding Journal, February 1942.

30. *Correct Procedures vs. Common Faults in Hand-Cutting,* H. H. Moss, The Welding Journal, February 1942.

31. *How to Cut Heavy Steel Sections,* R. B. Aitchison, The Welding Journal, June 1942.

32. *Factors Effecting the Accuracy of Machine Gas Cutting,* H. G. Hughey and A. H. Yoch, The Welding Journal, October 1942.

33. *Gas Cutting in Shipbuilding,* R. F. Helmkamp, The Welding Journal, December 1942.

34. *Planning for Production Welding and Cutting in a Modern Shipyard,* W. B. Bowen. The Welding Journal, November 1943.

35. *Flame Cutting Heavy Sections and Large Diameters,* R. L. Deily and E. Benyo, The Welding Journal, December 1943.

36. *Underwater Cutting and Welding,* H. L. Ingram, Jr., Marine Progress, May 1944.

37. *Practical Ways to Improve Machine Cutting,* H. H. Moss, The Welding Journal, June 1944.

38. *Underwater Cutting of Metal,* M. F. Rodman, The Welding Journal, July 1944.

39. *Flame Cutting Under Water,* G. R. Reiss, Steel, September 4, 1944.

40. *Fundamentals of Heavy Cutting,* G. L. Walker and H. G. Hughey, The Welding Journal, October 1944.

41. *Unusual Applications of Gas Cutting to Ordnance Fabrication,* C. M. Underwood, The Welding Journal, April 1945.

42. *Machine Gas Cutting,* R. M. Dennis, The Welding Journal, September 1945.

43. *Flame Cutting Stainless Steel,* G. E. Bellew, The Iron Age, July 11, 1946.

44. *Flame Cutting Operating Data,* A. F. Chouinard, The Welding Journal, December 1946.

45. *Heavy Cutting Applications in Foundry and Steel Mill,* R. S. Babcock, The Welding Journal, January 1947.

46. *Flux Injection Cutting Stainless Steels, Parts I and II,* G. E. Bellew, Steel, February 17 and 24, 1947.

47. *Powder Cutting and Scarfing of Oxidation Resistant Materials,* D. H. Fleming, Jr., The Welding Journal, March 1947.

48. *Oxygen Cutting of Steel at Elevated Temperatures,* J. F. Kiernan and J. S. Sohn, The Welding Journal, April 1947.

49. *Oxygen Cutting Stainless Steel-Oxyacetylene Powder Cutting and Scarfing,* D. H. Fleming, Jr., Steel, December 1, 1947.

50. *The Use of Flux-Injection Cutting for Stainless Steels,* G. E. Bellew, The Welding Journal, February 1948.

51. *Powder Cutting as a Production Tool,* D. H. Fleming, The Welding Journal, March 1948.

52. *The Powder Process in Stainless Steel Production,* C. J. Busch and E. M. Holub, Iron and Steel Engineer, July 1948; also abstracted in Blast Furnace and Steel Plant, April 1948.

CHAPTER 25

ARC CUTTING*

FUNDAMENTALS OF PROCESS

Definition and General Description

ARC CUTTING IS based on the conversion of electrical energy into heat within the confines of an electric arc maintained between the target and the electrode. This localized conversion, with a practical degree of control, is being utilized for arc cutting by three procedures, namely, the carbon-arc, metal-arc and arc-oxygen methods.

(*a*) The carbon-arc method is the simplest of the three procedures employing the heat generated by the arc to melt the metal progressively to produce the cut.

(*b*) The metal-arc procedure employs covered electrodes, which permit manipulation to accomplish the cut produced by the heat of the arc.

(*c*) The arc-oxygen procedure employs tubular electrodes, the arc serving to heat the metal to be cut to incandescence. The oxygen stream issuing from the bore of the electrode ignites the incandescent metal and the kinetic energy of the oxygen stream expels the products of combustion and produces the cut.

Principles of Operation

Carbon-Arc Cutting.—Carbon-arc cutting is a progressive operation performed by maintaining a steady arc length and a suitable rate of progression. The use of direct current, straight polarity is preferred for carbon-arc cutting for the following reasons:

(1) Higher heat is developed at the positive pole, which is the metal to be cut.

(2) The amperage required to obtain comparable cutting rates is about 10% higher with a.c. than with d.c.

(3) The maintenance of a steady arc, which is essential for effective cutting, is practicable in a d.c. circuit only when the electrode is negative to the work, since a relatively small area is essential to maintain the hot cathode condition.

Metal-Arc Cutting.—Metal-arc cutting is likewise a progressive operation employing covered, metal-core electrodes and preferably performed using direct current, straight polarity. The principal functions of the electrode covering in metal-arc cutting are to serve as a dielectric, thereby permitting insertion of the electrode into the gap of the cut without short circuiting the sides of the electrode, and to act as an arc stabilizer, thereby concentrating the arc and intensifying its action. Effectiveness of this procedure in cutting heavy thicknesses is a function of manipulation of the E6010, E6012 and E6020 electrode types. Electrodes with coverings specially designed tc facilitate cutting, are also available.

Arc-Oxygen Cutting.—The arc-oxygen method is the third, and, in degree of its development, the latest procedure for cutting metals progressively. The tubular electrodes used in arc-oxygen cutting are covered with an inert matrix to permit insertion into deep gaps when necessary. Again direct current, straight polarity is preferred. The function of the metal or ceramic core of the electrodes is to conduct current and maintain an arc of sufficient intensity to produce incandescence. By regulation of the oxygen pressure a sufficient volume of this gas is discharged through the arc to ignite the incandescent metal and to react with it; the kinetic energy of the excess oxygen removes the combustion products.

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General Effect of the Use of Process on Materials Cut

Metallurgical Effects.—The carbon- and metal-arc methods of cutting are essentially progressive melting procedures analogous to arc welding and in that respect the metallurgical effects produced in the affected zones are comparable to those which would occur in arc welding. Although the power input in arc cutting is usually higher than that normally employed in manual arc welding, the speed of travel is much faster. The heat penetration is generally shallower than in oxygen cutting and, therefore, there is a more pronounced quench effect. Metals which can be welded without requiring a postheat treatment, may be severed by arc cutting without detriment. Those grades of austenitic Cr-Ni steels which become sensitized to corrosion attack when shielded metal-arc welding is used are likewise adversely affected by arc cutting procedures. The power input rate employed in arc-oxygen cutting is lower than in carbon- or metal-arc cutting, and the metallurgical effects are, therefore, less pronounced.

Physical Effects.—The physical effects of arc cutting are similar to those obtained in oxygen cutting. Cast-iron and medium-carbon low-alloy steels are apt to develop cracks ranging in extent and depth from microscopic to those detectable by visual examination. In general, the extent and frequency of cracking is a function of the composition of these steels and also of the rate of power input. The higher the rate of power input, the lower is the cooling rate, and consequently, the lower the thermal stresses. Therefore, the occurrence of thermal fractures is minimized.

Chemical Effects. — The chemical changes resulting from arc cutting are similar to those produced by arc welding. However, except for slight surface decarburization in high-carbon alloys, the chemical changes are minor in comparison with the metallurgical and physical changes discussed above.

Warpage and Stress.—Under "Metallurgical Effects" it is stated that owing to the high power concentration obtained in arc cutting, heat penetration is shallow. Accordingly, the volume of metal adjacent to the cut which is subjected to a high rise in temperature, is also less than in oxygen cutting.

Since warpage is, in part, a function of the volume of metal raised to a higher temperature than that of the rest of the volume, distortion in arc cutting is less than in oxygen cutting. This characteristic of arc cutting renders it particularly suitable for cutting thin gage metal without undue warpage or buckling.

Machinability.—Machinability of low-carbon, mild steels and non-hardenable metals is not affected by any of the arc-cutting procedures. In cast-iron and high carbon steels, arc cutting may produce slight surface decarburization. Generally, this will not be of sufficient extent to reduce the hardenability of the base metal, and therefore the heat-affected zone will be characteristically hard and non-machinable. Likewise, in medium-carbon, low-alloy steels the heat effects of the cutting operation will generally cause hardening to such degree as to render the heat-affected zone unmachinable. The heating and cooling cycle to which the faces of the cut are subjected in arc cutting amounts to a very severe quench. Any alloys with sufficiently high hardenability may be expected to be left in a non-machinable condition in the heat-affected zone after arc-cutting operations.

Surface Conditions.—The surfaces obtained in arc cutting all thicknesses are generally rougher than in oxygen cutting. Whether or not the surfaces produced by arc cutting are suitable for further fabrication after trimming by chisel or grinder depends on the intended application. A variety of metals can be satisfactorily welded after arc cutting followed by normal trimming.

EQUIPMENT AND MATERIALS USED

Equipment

Carbon-Arc Cutting. — The power source for carbon-arc cutting is a d.c. welding generator, either the constant or the variable potential type. For currents up to 300 amp., air-cooled, carbon electrode holders are used. For currents in excess of 300 amp., water-cooled carbon electrode holders are desirable.

Metal-Arc Cutting.—For metal-arc cutting the applicable power sources are much the same as for carbon-arc cutting

although a.c. power is oftened used. For metal-arc cutting in air, standard electrode holders are applicable, employing heavy-duty types for use with $^{3}/_{16}$-in. diam. and larger electrodes. For metal-arc cutting under water, specially constructed, fully insulated electrode holders are mandatory; straight polarity must be used to protect the holders and the metal parts of the diver's outfit from electrolytic corrosion.

Oxy-Arc Cutting.—The same power sources are also applicable for oxy-arc cutting. Oxy-arc cutting may also be performed using a.c. welding transformers. The electrode holders employed for oxy-arc cutting in air and under water are not necessarily interchangeable, unless so designed. Those intended for use for underwater cutting must be fully insulated and must be equipped with a suitable flash-back arrester. These safeguards are also desirable for oxy-arc torches intended for use in air only.

Table 1—Current Values for Various Sizes of Graphite Cutting Electrodes

Electrode Diameter, In.	Current, Amp.
$^{1}/_{4}$	Up to 200
$^{3}/_{8}$	200– 400
$^{1}/_{2}$	300– 600
$^{5}/_{8}$	400– 700
$^{3}/_{4}$	600– 800
$^{7}/_{8}$	700–1000
1	800–1200

Auxiliary Equipment

Carbon-Arc Cutting.—For certain special applications, such as the removal of defective austenitic weld metal, carbon-arc cutting is used in combination with an air nozzle connected to a supply of compressed air. The nozzle is held back-hand in relation to the arc and the air stream issuing from it is directed to eject the molten metal from the groove.

Metal-Arc and Arc-Oxygen Cutting.—In connection with underwater cutting, using either the metal-arc or arc-oxygen method, the use of a disconnecting switch in the welding circuit is mandatory for the protection of the diver-operator. A double pole, magnetic switch is the preferred type. However, a double pole, manually operated disconnecting switch is admissible when there is a systematic exchange of telephoned signals between the tender and the diver-operator.

Carbon and Graphite Electrodes

Recommended current values for different sizes of graphite cutting electrodes are given in Table 1.

Solid Core Metal-Arc Cutting Electrodes

Solid core metal-arc cutting electrodes are produced in $^{1}/_{8}$ and $^{5}/_{32}$-in. diameters in 14-in. lengths and in $^{3}/_{16}$, $^{7}/_{32}$ and $^{1}/_{4}$-in. diameters in 18 and 14-in. lengths. Larger electrodes are not usually used because of their excessive spatter for which there is no effective protection.

Table 2, showing performance characteristics of solid core metal-arc cutting electrodes, is based on laboratory tests and is to be used only as a guide since the skill of the individual operator is a governing factor.

Tubular Core Oxy-Arc Cutting Electrodes

Steel Core Electrodes.—Tubular steel core electrodes are available in $^{3}/_{16}$- and $^{5}/_{16}$-in. diam. sizes with the bore diameter being approximately $^{1}/_{16}$ and $^{1}/_{10}$ in. respectively. The tubes are either seamless drawn or of open-seam construction. The $^{3}/_{16}$-in. diam. tubes are 18 in. long; the $^{5}/_{16}$-in. tubes are 14 in. long. The covering is extruded to a thickness comparable to that of mild-steel electrodes conforming to AWS Classification E6013. For

Table 2—Performance Characteristics of Solid Core Electrodes for Metal-Arc-Cutting Steel Plates

Electrode Diameter, In.	Plate Thickness In.	Cutting Rate, In./Min.	Current, Amp.	Length of Cut for Electrode, In.	Time to Consume Electrode Min.
$^{1}/_{4}$	$^{1}/_{4}$	10	400	10	1
$^{1}/_{4}$	$^{1}/_{2}$	4	400	4	1
$^{1}/_{4}$	$^{3}/_{4}$	2	400	2	1
$^{3}/_{16}$	$^{1}/_{4}$	5	300	5	1
$^{3}/_{16}$	$^{1}/_{2}$	3	300	3	1
$^{3}/_{16}$	$^{1}/_{4}$	12	400	9	$^{3}/_{4}$
$^{3}/_{16}$	$^{1}/_{2}$	6	400	4	$^{3}/_{4}$
$^{3}/_{16}$	$^{3}/_{4}$	3	400	2	$^{3}/_{4}$

underwater use the electrodes are given a final coating with a thermo-plastic which renders the covering impervious to fresh or sea water for several hours of immersion even at depths exerting a static pressure of 100 psi.

Ceramic Core Electrodes.—Ceramic core electrodes are produced in one size only, namely, 1/2-in. diam., 1/8-in. bore, 8 in. long. The ceramic core is composed of a silicon compound which is an electrical conductor. The electrode cores are annealed to increase their resistance to heat shock and, to withstand mechanical shock better, they are encased in a steel sheath of approximately 1/32 in. thickness generally applied by metallizing. The final processing is the application of a glass cloth sleeve which is saturated with a thermo-plastic set at a relatively low temperature. The plastic material serves as an electrical insulator.

Table 3 is an extract from the Bureau of Ships, Navy Dept. Specifications 46E6 (INT) for *Tubular Underwater Cutting Electrodes* for use with the arc-oxygen process wherein the *minimum* requirements are defined as shown.

the carbon arc or with the metal arc does not require any other manipulation than maintaining the arc between the electrode and the metal being cut and advancing it as the gap progresses. The manipulation used to cut heavier thicknesses consists of a dipping motion to displace the molten metal.

In oxy-arc cutting there is normally no manipulation. Cutting in air (3 in. of mild steel or 1/2 in. of certain nonferrous alloys), with 3/16 or 5/16-in. diam. steel tube core electrodes, the technique is to drag the electrode along the intended line of cut applying slight pressure. In cutting underwater, regardless of the thickness of the metal being cut, positive pressure must be maintained against the metal being cut. In cutting underwater with tubular ceramic core electrodes, the pressure is light but must still be positive and continuous. Piercing in air or under water is by striking an arc and pushing the electrode into and through the metal being pierced. The coating insulates the electrode core from shorting against the sides of the hole.

The comparative performance with

Table 3—Minimum Requirements for Tubular Underwater Cutting Electrodes for 1/2-In. Steel Plate

Electrode Material and Size	Cutting Rate In./Min.[a]	Cut/Burnoff Ratio[b]	Power		Oxygen Pressure, Psi.
			Amp.	Volts	
Steel Tube Core,[c] 5/16 In. Diam.	18	1	300	37–40	30
Ceramic Tube Core,[d] 1/2 In. Diam.	10	15	350	30	30

[a] Includes time required for piercing plate at start of cut.
[b] Cut/Burnoff Ratio = Linear inches of metal cut per inch of electrode consumed.
[c] Minimum requirements.
[d] Tentative minimum requirements.

Table 4 is an extract from the Bureau of Ships, Navy Dept. *Manual for Underwater Cutting and Welding* giving the length of cut per electrode based on the results obtained in acceptance tests rather than in field applications.

Table 4—Length of Cut per Electrode for 1/2-In. Steel Plate

Electrode Material	Length of Cut per Electrode, In.	Time to Consume Electrode
Steel tube core	12	40 sec.
Ceramic tube core	100	12 min.

HOW TO CUT

Cutting thin plates (under 1/2 in.) with carbon-arc, metal-arc and oxy-arc cutting in air and under water is presented in Table 5.

COMMON APPLICATIONS

Carbon-arc cutting, being the least expensive of the arc-cutting procedures and the one which is least amenable to control as regards the appearance of the cut edges, is used mostly in scrapyards; it is also used to some extent to remove risers and gates from nonferrous castings. It is used in yards for cutting both light and heavy sections of steel, using heavy-duty electrode holders for the latter type of work. Metal-arc cutting employing covered welding electrodes processed with waterproofing has had some appli-

cation as an emergency procedure for underwater cutting. Solid core electrodes with special coverings designed to accelerate the cutting rate are being used for the cutting in air of nonferrous metals, particularly risers and gates of bronze castings. If the proper technique is used, these electrodes are capable of cutting metals of any shape or geometry. The thickness of metal that may be cut with them is a function only of the useful length of the electrodes, which are produced in 14 and 18-in. lengths.

Fields or Industries in Which Arc Cutting Is Commonly Used or Is Applicable

Carbon-arc cutting is used occasionally in scrapyards and in dismantling structural steel assemblies. Carbon-arc cutting is not used when it is desired that the cut have a finished appearance, except for light gage applications.

Metal-arc cutting is used for cutting risers and gates in nonferrous foundries and to cut up heavy, nonferrous scrap for remelting. Covered electrodes with a waterproof coating of lacquer or plastic have at times been used as emergency material for underwater cutting. The cut produced by metal-arc cutting is less ragged than in carbon-arc cutting, but generally it is not satisfactory preparation for welding without considerable trimming by chiseling or grinding.

Oxy-arc cutting using tubular electrodes was developed primarily for underwater cutting; and is gaining increasingly wider application in surface cutting. Oxy-arc cutting is used effectively for cutting mild and low-alloy steels and also stainless steel, cast-iron and the nonferrous metals in all positions and its value varies with thickness and composition of the material. The edges cut by the oxy-arc torch are somewhat uneven and require a light surface preparation in order to be made suitable for welding.

Table 5—Comparative Cutting Rates for 3/8-in. Thick Mild Steel Plate

Method	Electrode Diam., In., Type	In Air: Current, Amp.	In Air: Oxygen Pressure, Psi.	In Air: Cutting Rate, In./Min.	Underwater: Current, Amp.	Underwater: Oxygen Pressure, Psi.	Underwater: Cutting Rate, In./Min.
Carbon arc	3/8 Carbon	300	..	5	300	..	2
Metallic arc	3/16 Steel	300	..	8	300	..	6
Arc oxygen	3/16 Steel tube	175	75	45	...	..	..
Arc oxygen	5/16 Steel tube	300	30	45	300	30	27
Arc oxygen	1/2 Ceramic	...	..	..	350	30	15

The above values are based on laboratory tests and field experience and are to be used only as a guide.

Oxy-arc cutting electrodes were developed primarily for use in underwater cutting and were later applied for cutting in air. In both applications they are capable of cutting both ferrous and nonferrous metals, in practically any thickness and position. Ceramic core, arc-oxygen electrodes are not effective for cutting metals heavier than 1 in. in thickness. Oxy-arc cutting devices are at present gaining wider use as stand-by shop equipment or to complement oxygen-cutting torches, particularly for piercing steels, cutting cast-iron, nonferrous metals, stainless steels and loosely faying plate or sheet assemblies, for which ordinary oxygen-cutting torches are less satisfactory if not unsuitable. The versatility of oxy-arc cutting, using both steel and ceramic tube electrodes, was proved by the Naval Service during World War II. Extensive field tests have since gained acceptance of the procedure and materials by industrial users.

BIBLIOGRAPHY

1. *U.S. Navy Developments in Underwater Cutting*, Bela Ronay and C. D. Jensen, Journal American Society of Naval Engineers, November 1945. (Reprinted in The Welding Journal, March 1946.

2. *Underwater Cutting and Welding*, Charles Kandel, The Welding Journal, March 1946.

3. *Underwater Cutting and Welding Speeded and Simplified by Electric Arc Process*, Charles Kandel, Engineering News-Record, April 4, 1946.

4. *The Theory of Oxyarc Cutting*, H. C. Campbell, The Welding Journal, October 1947.

5. *U.S. Navy Underwater Cutting and Welding Manual*, 1948 Edition.

CHAPTER 26A

OXYGEN MACHINING PROCESSES*

FUNDAMENTALS OF PROCESSES

Definition and General Description

OXYGEN MACHINING includes those processes wherein oxygen is used in the surface removal of metals. These processes are shown in Fig. 1. A brief description of each follows:

Scarfing or Deseaming.—This process is used for the removal of cracks or surface seams, scabs, scale and other defects on the surfaces of blooms, billets, ingots, bars and other unfinished shapes in steel mills during the mill cycle and before these shapes reach the finishing departments.

Gouging.—This process is used for the removal of defective welds or tack welds and the removal of welds in scrapping operations, or in the removal of weld metal to sound metal in the root of a weld. It is also used in the elimination of defects such as cracks, sand inclusions and surface porosity from steel castings. The three methods of using this process are progressive gouging, backstep gouging and spot gouging.

Hogging.—This process is becoming increasingly important for use in the foundry for the removal of superfluous metal from steel castings. It is used for the removal of risers and sprues, which are often of such a nature or so located that they are difficult or impossible to remove by ordinary oxygen-cutting methods. Riser washing to remove excess metal prior to the final grinding operation is an application of hogging.

Surface Planing.—This process is very similar to a mechanical planing operation, the main difference being the substitution of an oxygen jet for the planing tool. Surface planing can be used for the removal of metal from either flats or rounds by a series of parallel, overlapping grooves, with close dimensional tolerances on depth and width of individual cuts.

Oxygen Turning.—This process is identical to the mechanical operation of turning, with the substitution of a cutting

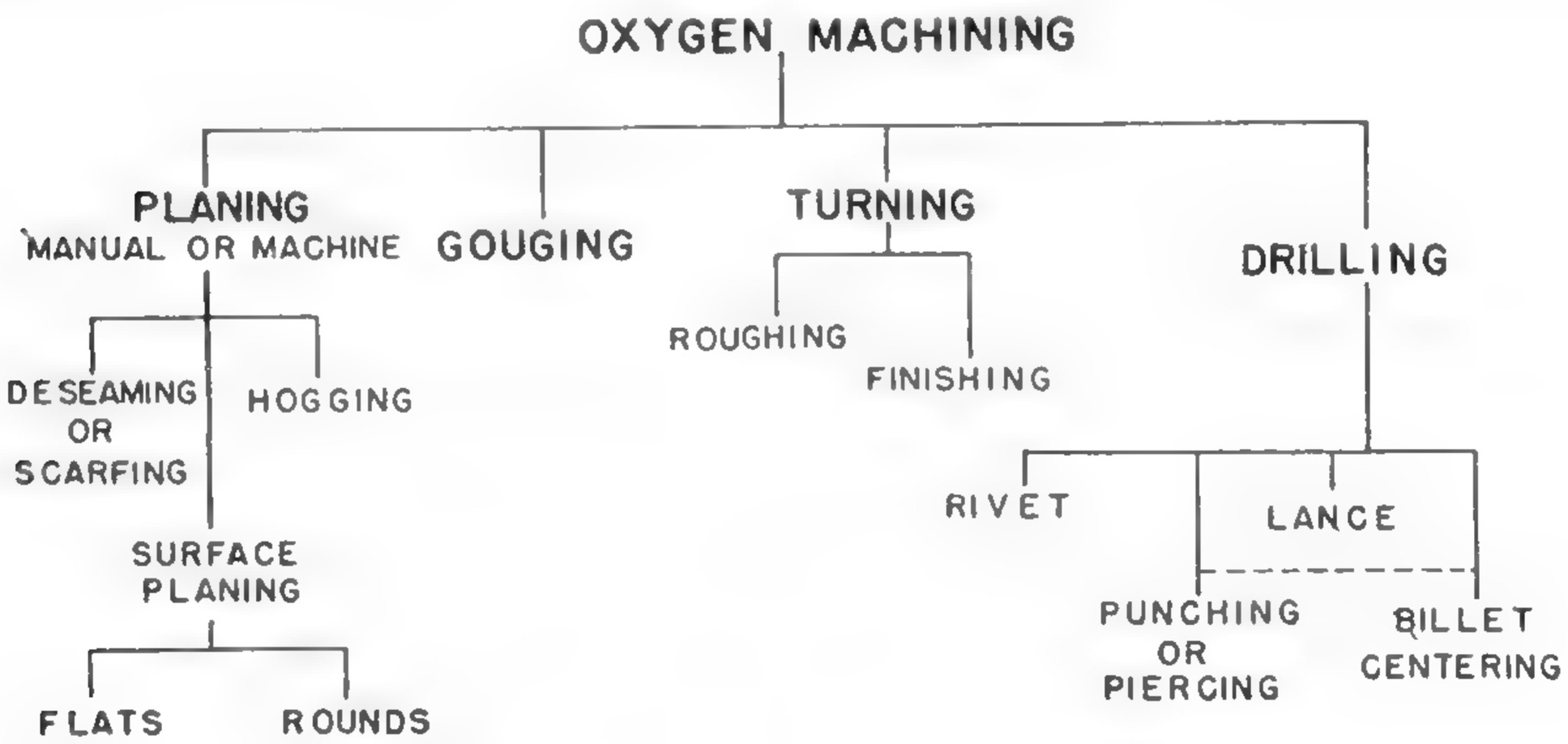

Fig. 1.—Chart of Oxygen Machining Processes

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torch mounted on the carriage of a lathe in place of the usual cutting tool and tool post and with the work mounted between centers of the lathe in the same manner as for mechanical turning.

Oxygen Drilling.—Drilling may be divided into rivet removal, lancing and punching.

Rivet removal is accomplished by a cutting-oxygen stream which washes a crater in the rivet head and finally consumes it, permitting the rivet to be knocked out on the opposite side.

Lancing may be used for piercing holes in steel. It is used for this purpose in a manner similar to oxygen-lance cutting, which is described in Chapter 24.

Punching or piercing is a form of drilling whereby a standard cutting torch is used to form a depression in the surface of a billet either for centering or final piercing. In the latter case, a lance is used when a depth beyond the reach of a standard tip is attained.

Principles of Operation

Chemistry.—Since the chemistry involved in the removal of steel by oxygen machining is exactly similar to that of the oxygen cutting process, this information will not be repeated but reference is made to the section on Chemistry of Oxygen Cutting in Chapter 24. The affinity of oxygen and iron at an elevated temperature is employed to oxidize the metal at the surface, and the resulting slag consisting of oxidized metal and molten iron is swept clear of the reaction zone by the force of the issuing jet of oxygen. The chemical reaction is identical to that described for oxygen cutting.

Torches and Tips.—The principles of operation of oxygen-machining equipment are the same as for oxygen cutting. The differences will be found to be in the design of the individual pieces of apparatus to give the desired result in the type of groove or surface removal of metal, and in the technique employed. The basic equipment consists of a torch and a suitable tip mounted in the head of the torch. Preheating gases are conducted through a series of orifices usually arranged in a concentric circle about a central orifice of fairly large diameter. A stream of oxygen at a relatively low velocity issues from this central orifice. The success of the process is due to the design of a special nozzle to deliver a relatively large volume of oxygen at a low jet velocity.

Effect of Oxygen Purity.—The same considerations regarding the importance of high purity oxygen, discussed in Chapter 24, pertain to these processes with equal force. Since the basic chemical reaction is identical, it is to be expected that oxygen purity will be of equal importance. In fact, since oxygen machining is a means of surface removal of steel in advance of the tip and in an area somewhat removed from the influence of the preheating flames, it is even more essential that the oxygen purity be maintained at a high level to insure that the thermal balance is maintained to prevent the loss of the cut.

Preheat Fuel.—Acetylene is by far the most widely used fuel gas for oxygen-machining operations. As explained in Chapter 24 the preheat flame serves two functions: (1) to raise the temperature of the steel initially up to its kindling temperature and (2) to maintain a thermal balance during the cutting operation. Acetylene is ideally suited because of its high flame temperature which makes rapid starts possible. Speed in starting, especially in scarfing, is an important factor in high production applications such as in a steel mill where the savings in time and labor of a quick start may well exceed the economies of using a cheaper fuel gas.

However, fuel gases other than acetylene are extensively used in those localities where these other gases are readily available. Such fuel gases as propane, natural gas and city gas (manufactured gas) have been used for oxygen machining as well as for cutting.

Scarfing Technique

Manual.—The actual technique for manual scarfing is difficult to describe, and can only be learned by practice and familiarity with the process and the equipment. However, facility in manipulating the torch is readily acquired, and a few days instruction suffices for the average operator to become reasonably skilled.

In brief outline, the technique is as follows: First, a spot on the surface is heated to the ignition temperature. When preheating, which also melts off the surface scale and exposes clean metal, the torch is held at an angle of about 75 deg. to the work, with the tips of the preheating flames touching the metal surface. The

preheated area should be as extensive as possible to assure rapid starting and to prevent excessive digging at the beginning of the scarf. When the steel has reached the proper temperature and with clean metal exposed, the tip is drawn back about an inch and the angle between the torch and work reduced. This places the tip in position so that the oxygen stream will impinge upon the preheated area when the oxygen valve is opened. The operator now gives the torch a forward motion of about $^1/_2$ to $1^1/_2$ ft. per sec., and at the same time depresses the oxygen valve. If a starting rod feed device is being used for ease in starting, depressing the lever of the oxygen valve will also actuate the rod feed and advance a portion of the starting rod into the path of the oxygen stream. The combustion of the sections of rod liberates heat, and the products of combustion which are thrown against the steel surface facilitate the start of the reaction on that surface. Proper timing of the forward motion of the torch, change in tip angle and opening of the cutting-oxygen valve permit the realization of shallow starts equivalent to sharp chisel cuts. Preheating is unnecessary when starting rods are used.

After the scarf has commenced, the forward motion of the torch must be continued without interruption or hesitation. However, during the forward motion it is possible to alter the inclination of the tip to the steel surface so as to control the width and depth of the scarf.

When an entire surface is to be scarfed and a series of adjacent passes are required the first should be made nearest the operator. Subsequent passes should then be made on the far side of the previous scarf. By holding the tip slightly angled away from the operator or toward the right of the direction of travel (when traveling from right to left), the oxide will be washed to the far side of the scarf, and succeeding passes of the torch will remove the oxide remaining from the preceding scarf. This lateral angling of the tip also results in a wider and shallower scarf without excessive fins remaining on either side of the scarf.

If the tip is held in a direct line with the direction of forward motion, a deep, narrow scarf results, and the slag removed from the scarf is blown to both sides, forming parallel fins on the surface, which frequently require further cleaning.

A properly scarfed surface after successive passes of the torch is covered by a light, flaky oxide coating which may be easily removed by a wire brush revealing a finished surface which is bright and clean. If any defects remain, they will be clearly visible on the surface and can be readily marked for additional treatment. The finish is comparable to that of steel cleaned by chipping.

Mechanical.—By placing the scarfing torches on machines, and by providing relative motion between the machine and the work-piece, it is possible to mechanize the process and to obtain the inherent benefits of the process together with those of mechanized operation. Because of the economics involved, mechanical scarfing is only feasible for large-scale scarfing operations such as encountered in steel mills.

Gouging Technique

As in oxygen cutting, it is first necessary to bring the steel in a small area up to its kindling temperature. This is accomplished by allowing the preheating flames to play on the spot where the gouge is to be started, the torch remaining stationary until the ignition temperature has been reached. With the tip held at a small angle to the work, the valve controlling the oxygen stream is opened slowly, and the torch and tip are then moved slowly in the direction of the gouge. At the same time the angle of the tip is gradually reduced to the correct operating position. The techniques for the three methods of gouging—progressive, spot and backstep—are discussed separately below.

Progressive Gouging.—In the progressive method of gouging, the correct tip or nozzle is first selected depending on the size of the desired gouge. This may be based upon the experience of the operator or from Table 1 and the oxygen pressure is then regulated to give the desired width and depth of groove. The data in Table 1 apply for average conditions, and for best results selection of the optimum operating conditions should be obtained by trial.

In starting the gouge the torch is held with the end of the tip or nozzle, at an angle of approximately 20 to 45 deg. to the work above the line of the gouge, as shown in Fig. 2. The torch is held so that the tips of the inner cones of the preheat flames are just touching the work. The preheat flames are played on the spot

where the gouge is to be started, until the surface reaches the ignition temperature. The angle between the tip and the surface is then reduced to between 15 and 20 deg. and simultaneously the tip is withdrawn so that the inner cones of the preheat flames are from $^1/_4$ to $^1/_2$ in. behind the preheated area (see Fig. 3). The oxygen control lever is also gradually depressed, and the torch is advanced as soon as the reaction starts. The gouge progresses slowly while the angle of the end of the tip is gradually reduced to the correct operating position. This angle will be readily discernible by the operator. If the tip is not lowered far enough some of the slag will tend to flow backward into the gouge toward the operator; if it is lowered too far, the gouge will become shallow and will soon be lost. Best results are obtained when the torch is held so that the tip clears the bottom of the groove. Figure 4 shows a close-up view of the operation in progress. About 2 ft. per min. is the approximate speed of travel of the torch in making the clean gouge shown in Fig. 4, $^3/_8$-in. wide and $^1/_4$-in. deep, in steel plate.

When it is necessary to change the direction of the cut, the angle of the tip in relation to the work should remain unchanged while the torch is rotated to the new direction. Too sharp a turn should be avoided lest the outside wall be cut into as the result of the action of the molten slag. It is advisable to use lower oxygen pressures than those indicated in Table 1 when not gouging in a straight line.

The depth of the gouge is a function of the speed of progression and the angle between the oxygen stream and the work. To cut a deep gouge the angle of the torch is increased in relation to the gouge and the speed is correspondingly decreased. In order to make a shallow gouge the procedure is reversed. With the establishment of the correct depth of gouge, it is an easy matter to maintain this depth throughout the full length. Gouges can be made that are as deep as or slightly deeper than they are wide. Furthermore, successive passes can be made to reach the bottom of a defect that may be as much as 2 to 3 in. below the surface.

The contour of the gouge is dependent upon the characteristics of the tip used and the operating conditions. If the oxygen pressure is too low, the gouging action will be very shallow and slow. Too high an oxygen pressure will require rapid tip movement to prevent a deeper gouge than is desired or even piercing through the plate.

Backstep Method.—The backstep method was developed during the war to facilitate removal of defective welds. The backstep method of gouging is similar to the progressive method in positioning the tip and preheat. After the starting point has been heated to the ignition temperature, the oxygen valve lever is depressed and the tip moved in the line of gouge but in a backward instead of a forward direction for $^3/_4$ in. while gradually increasing the angle between the tip and the plate. The oxygen valve is then closed and the torch moved forward along the proposed line of gouge for approximately $1^1/_4$ in. while maintaining a puddle of molten metal with the preheat flames. The oxygen valve is again opened and the torch drawn backward until the gouge made by the preceding pass has been reached. This intermittent sequence and the rocking motion produced by inclining

Table 1—Operating Data for Gouging Equipment

Tip Diam., In.	Oxygen Regulator [a] Pressure, Psi,	Consumption, Cu. Ft./Hr.			Approximate Speed, Ft./Min.	Approximate Gouge Dimensions, In.	
		Acetylene	Preheat O_2	Cutting O_2		Width	Depth
0.130	65	35–38	35–38	78–82	1.0–1.2	$^5/_{16}$	$^1/_8$–$^3/_{16}$
0.130	70	35–38	35–38	88–92	1.4–1.6	$^5/_{16}$	$^5/_{32}$–$^7/_{32}$
0.130	75	35–38	35–38	98–102	1.5–1.8	$^5/_{16}$	$^3/_{16}$–$^1/_4$
0.190	80	50–55	50–55	170–175	1.6–1.9	$^3/_8$	$^3/_{16}$–$^1/_4$
0.190	85	50–55	50–55	188–192	1.8–2.0	$^7/_{16}$	$^7/_{32}$–$^9/_{32}$
0.190	90	50–55	50–55	205–210	1.9–2.2	$^7/_{16}$	$^1/_4$–$^3/_8$
0.250	90	55–60	55–60	278–282	1.9–2.2	$^1/_2$	$^3/_{16}$–$^1/_4$
0.250	95	55–60	55–60	308–312	2.3–2.6	$^1/_2$	$^1/_4$–$^3/_8$
0.250	100	55–60	55–60	328–332	2.5–2.8	$^1/_2$	$^5/_{16}$–$^7/_{16}$

[a] Pressures measured at the regulator; acetylene pressure 10 psi. in all cases. Tips can also operate on low-pressure acetylene.

the torch is repeated along the entire length of the defective section of the weld.

Spot Gouging.—In spot gouging, for the removal of a single weld defect, the defect is first marked out in the surface of the weld. A starting point is next selected a little to the rear of the mark, depending on how deep the defect is judged to be. The gouge is then started in the usual manner by preheating the spot, but instead of reducing the angle of the tip, it is increased gradually so that the oxygen jet is directed downward until the gouge has penetrated to the depth of the defect. As in scarfing or deseaming, a little experience enables the operator to observe readily any defects, which appear as dark spots in the molten zone.

surface removal desired. The rate of feed is adjusted to provide suitable overlap of the reaction zones.

Rivet Washing Technique.—In addition to rivet cutting mentioned in Chapter 24, there is a second method for removing rivets using the cutting torch. This is usually named rivet washing to differentiate the process from the purely cutting operation. In rivet washing, the rivet is removed by using the cutting torch to consume the rivet head by a *washing* action, repeatedly manipulating the torch until the entire rivet head has been oxidized. With the rivet head destroyed, the rivet is then punched out. The slag resulting from the washing action is removed by the kinetic energy of the cutting

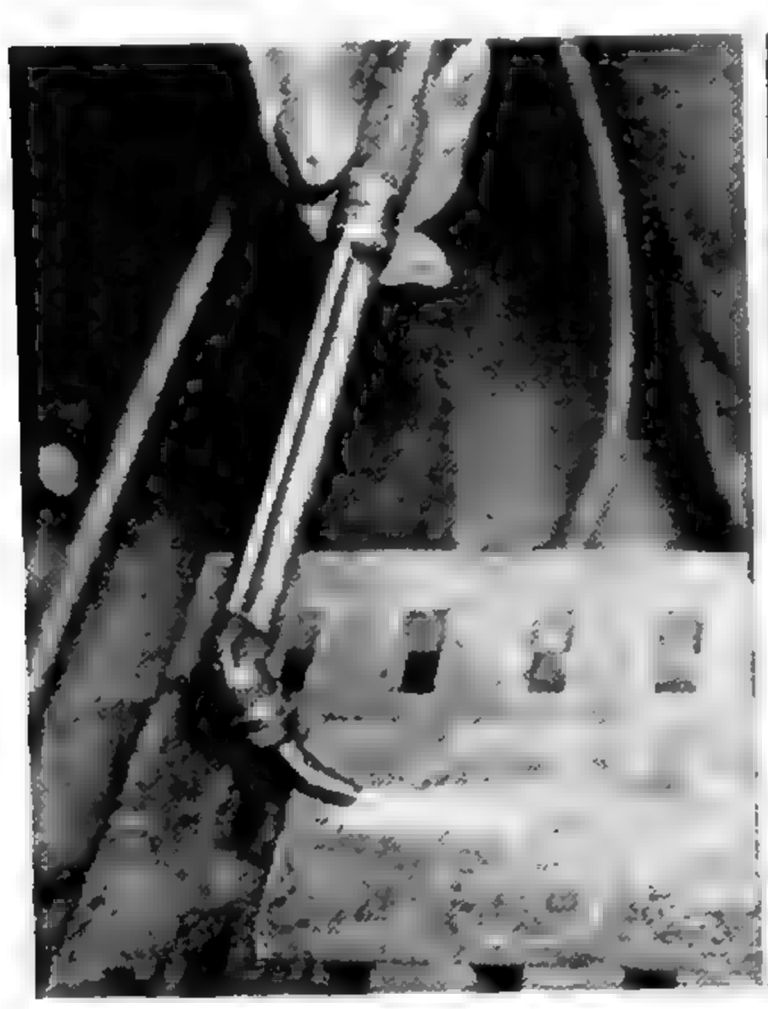

Fig. 2.—Correct Angle of Tip for Starting a Gouge

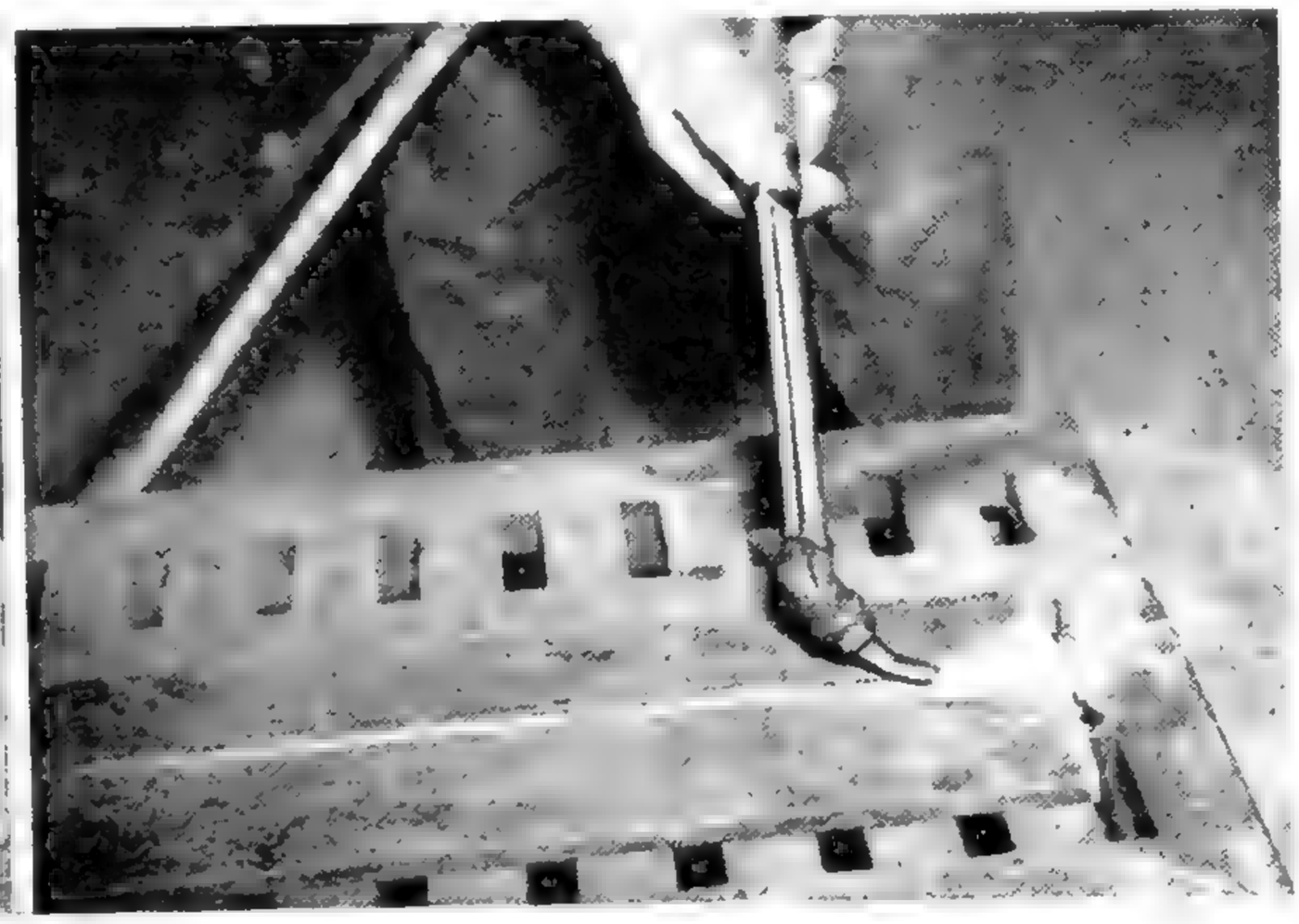

Fig. 3.—Correct Angle of Tip for Continuing a Gouge

The torch should be held so that the tips of inner cones of the flames are about $^1/_{16}$ in. above the plate surface at all times during the operation. The resulting gouge is narrow and U-shaped and can readily be filled with a minimum amount of weld metal.

Hogging Technique.—The techniques used in hogging operations are a combination of scarfing and gouging techniques. The actual techniques to be used for specific applications will vary from one application to another.

Surface Planing and Turning Technique.—The technique for this operation is the same as for scarfing. Having mounted the work in a planer or lathe, the torch is adjusted to the proper angle and distance to provide the extent of

jet. The technique cannot be described adequately but can be acquired fairly readily by practice. Results can be obtained by an experienced operator such that the plate remains undamaged and unmarked by the torch. As the shank of the rivet is merely punched out, the diameter of the hole in the plate is unchanged. Thus, the process of rivet washing finds wide application when the plates and existing rivet holes are to be reused.

Punching

Billet Centering.—Billet centering is a form of punching or piercing using a large size cutting tip. The center of the billet end is heated to the ignition temperature and a burst of oxygen then forms a crater in this surface. The size of the

hole depends upon the size of the oxygen orifice, duration of oxygen flow and oxygen pressure. The preheating time and hole-forming time depend upon the material temperature. Small holes (1-in. deep by 1 in. in mouth diam.) in hot steel may require only 1.2 sec. preheat time plus 0.5 sec. oxygen piercing time while larger holes (3-in. deep and 2 in. in mouth diam.) on cold material will require 7 sec. preheat time plus 7.5 sec. piercing time. The tips have a large number of preheat ports uniformly spaced around the oxygen orifice to produce round centers. Portable and stationary billet centering machines are used for production operations. The short duration of preheat and piercing time on hot steel requires automatic timing devices to reproduce uniform centers.

Effects of Oxygen Machining on Material

Chemical.—The chemical effects due to oxygen machining are similar to those due to oxygen cutting. For a discussion of these effects refer to the section on chemical effects in Chapter 24.

In general, the chemical effects are slight and hardly noticeable. They do not interfere with the usual processes used subsequent to oxygen machining. Thus a defect in a weld or a casting removed by gouging will be rewelded in a later operation. In the case of billets and slabs scarfed in a steel mill, the subsequent reheating for rolling will produce oxidation and scaling of the surface much more pronounced than the chemical effects of the scarfing process itself.

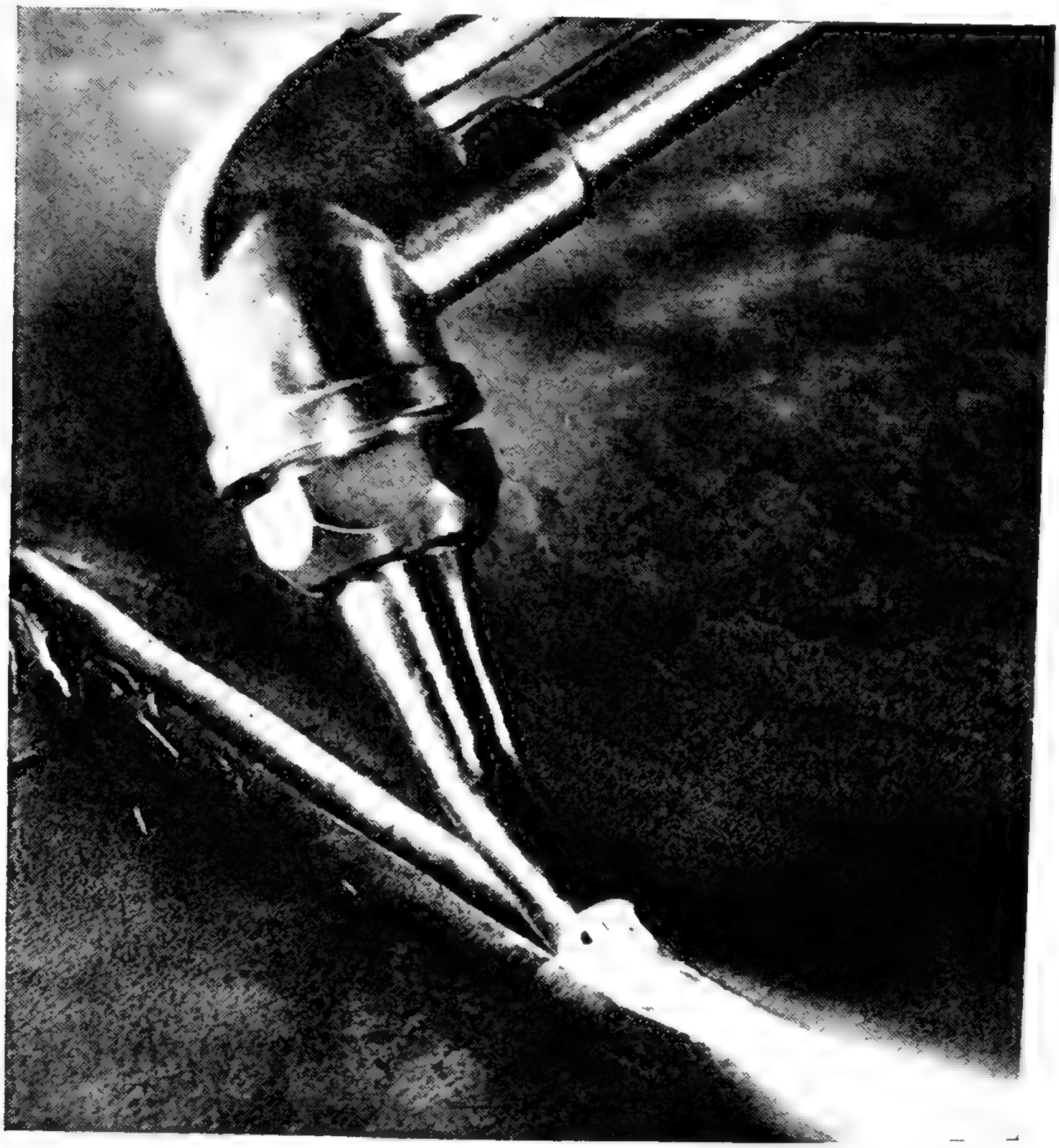

Fig. 4.—Close-up of Gouging Operation

Metallurgical.—In Chapter 24 the effect of oxygen cutting on the metallurgy of steel was discussed. These same considerations apply to the oxygen machining processes. The metal being removed is at a temperature approaching its melting point, and consequently, the steel immediately adjacent to the reaction zone is heated well above its critical temperature, while the mass of metal at some distance from the operation is not affected appreciably. These conditions then represent typical hardening conditions for the metal in the vicinity of the reaction with a large temperature gradient from the reaction zone to the cool mass of metal. Due to the high coefficient of heat transfer through steel, the hardening action is even more drastic than that of a normal water quench. Proper precautions are necessary to prevent checking and cracking of the steel surfaces. This is especially true where large billets or castings are being scarfed.

To determine whether special precautions are needed to prevent checking and cracking, the analysis of the steel should be known. With a knowledge of the analysis, it is possible to determine the hardenability of the steel, and so to predict the likelihood of checking and cracking. The same considerations as discussed in Chapter 24 under Metallurgical and Physical Effects, and Heat Treatment are equally valid for oxygen machining.

For the most part, oxygen machining can be employed on practically all grades of carbon and alloy steels except for certain of the austenitic stainless, and corrosion-resistant steels for which the flux or powder processes may be necessary. High-carbon or alloy steels must be preheated sufficiently to reduce the stresses set up on cooling. This is very necessary when oxygen machining alloys containing nickel or chromium. In steel mills where billets are scarfed prior to the rolling operations, scarfing is often done by machine in the roll line at temperatures between 1600 and 2000°F. However, for many steels preheat temperatures to 400°F. and in some cases to 900°F. have been found to be adequate. Many analyses may be scarfed cold without danger of cooling cracks. In practice it is preferable to determine the required preheating temperature as a result of experience with the particular grade of steel. Some borderline steels require preheating in winter but not in summer months.

Alloying Elements.—As has been previously stated, oxygen machining may be done on practically all grades of steels with the exception of corrosion- and heat-resistant alloys and some tool steels, provided adequate preheat is used for those alloys subject to stress cracking and checking. In general, the various alloying elements will have substantially the same effects as they have in oxygen cutting.

High-carbon steels are scarfed without difficulty if preheated. Such steels have been successfully scarfed with the carbon content as high as 1.36%. High-carbon steels containing nickel or chromium up to 3% are scarfed as regular commercial practice. Manganese as an alloying element is not detrimental; steels with a manganese content as high as 10.5% are handled easily. High-manganese steel with high sulfur content does not prove troublesome. Silicon in the amounts usually found in steel does not appear to be detrimental.

When high percentages of alloying elements are present, preheating may be necessary. This is particularly true for steels containing nickel or chromium. It should be noted that any steel that can be oxygen machined at room temperature with good results may also be handled successfully at an elevated temperature. Consequently, if the effect of an alloying element is in doubt, it is advisable to preheat the material.

Quality of Oxygen-Machined Surfaces.—The desired contour of the surface depends to a large degree on the service or purpose for which the material is intended. In work such as gouging for removing defects prior to rewelding, it is desired to produce a smooth, accurately defined groove of relatively narrow width. In this case it is required to gouge out the defect with a minimum removal of adjacent sound metal, consequently a narrow, deep groove is the ultimate aim. Other work, notably that classified under the headings of Surface Planing and Turning requires the removal of metal in wide, flat, shallow gouges without the formation of ridges or fins between the various passes. Other oxygen machining processes require surface contours intermediate between these two extremes. As examples, the shaping of a large shaft to fit a wobbler plate in the drive mechanism

of a steel mill roll assembly and gouging a J-groove in the edge of a plate as preparation for welding may be cited to indicate various requirements of the oxygen machining process.

By proper selection of equipment and by using the correct technique, all of these requirements for finish contour can be obtained. Different types of contour used in various oxygen-machining operations are sketched in Fig. 5. Typical gouging operations on arc welds are depicted in Fig 6. The dotted lines show the metal removed by gouging. It should be noted that the U-grooves shown in Figs. 6*A* and 6*C* are also produced by oxygen gouging.

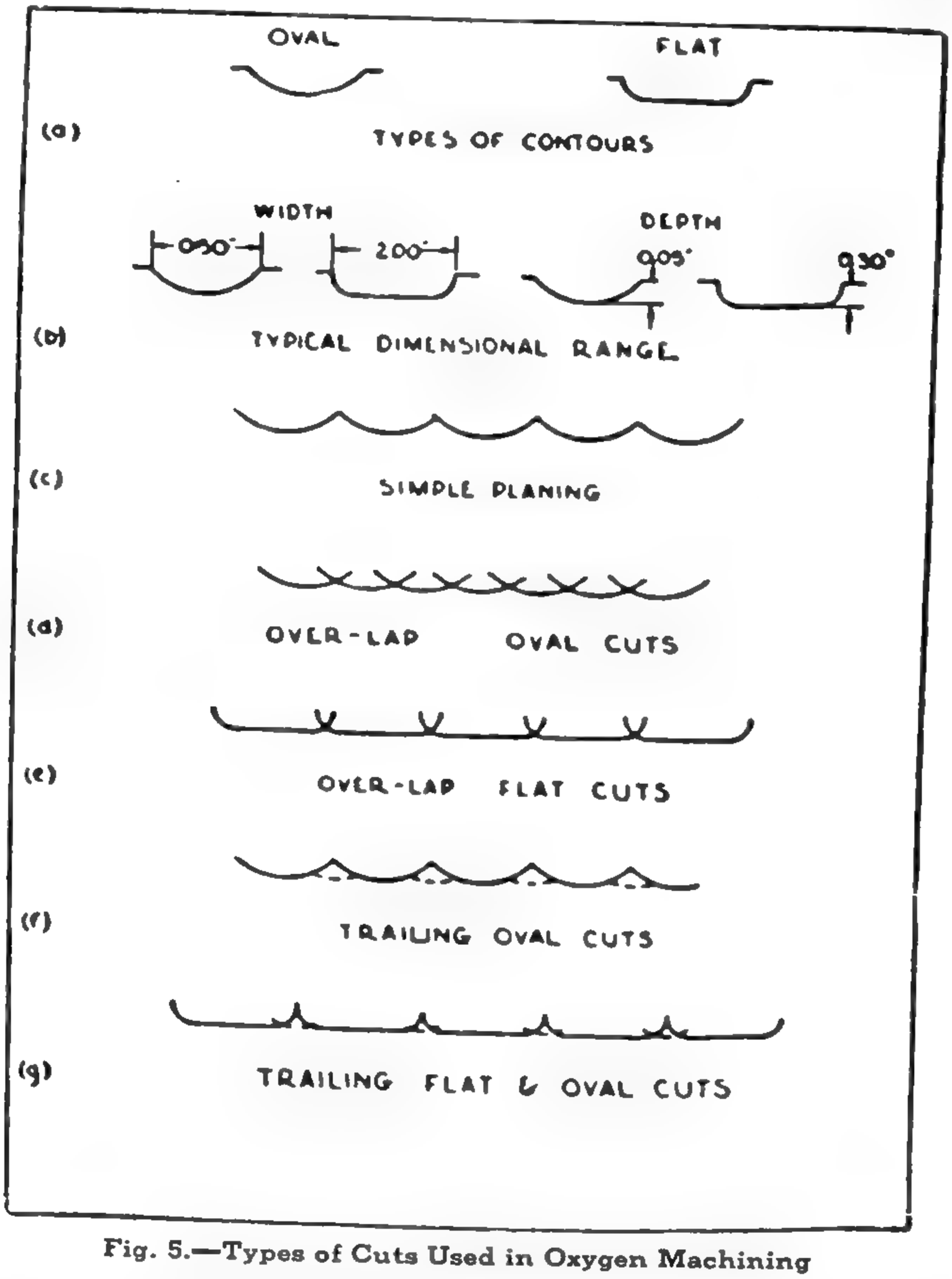

Fig. 5.—Types of Cuts Used in Oxygen Machining

EQUIPMENT USED

Manual Scarfing and Gouging

In many respects the equipment used for manual scarfing and gouging is similar to that used for manual cutting operations. The torch used for gouging serves the same function as does the cutting torch, that of conducting the gases to a suitable tip. The principal characteristic of the scarfing torch is its ability to handle large gas volumes as required by the scarfing process. Other differences are mainly dimensional, the scarfing torch being longer than a cutting torch in order to enable the operator to manipulate it without undue fatigue. While a cutting torch may have an average length of about 24 in., scarfing torches are available in lengths ranging from 36 up to 72 in. or more to permit easy handling of work at floor level from a standing position. Torches with heads inclined at various angles are commonly employed, the choice depending upon the location and nature of the application. Heads at 90-, 75- and 45-deg. inclinations with the axis of the

torch and also in line with the torch are most common.

Selection of the appropriate tip to be used for a particular application is the most important consideration in oxygen-machining operations. For surface-scarfing and surface-planing operations the tip is designed to remove metal from a wide area but to a shallow depth. Other tips are available to make a narrow groove which with proper technique can be used to produce a gouge of considerable depth. Such a tip would be required to remove deeply located defects in welds or porosity in castings, where it is desired to remove a minimum amount of metal so as to require a minimum amount of rewelding to correct the defect. Tips for different fuel gases are also available; special skirted tips are used for propane and other hydro-carbon fuel gases.

which at the direction of the operator feeds the heated end of a mild steel rod into the path of the cutting oxygen above the intended location of the reaction zone for ease of starting the cut. Such a means for commencing the cut tends to eliminate deep digging when starting a scarf. Likewise, for spot gouging where it is desired to remove a defect from a small area, the starting rod feed device will be found useful in affording control for the proper manipulation of the torch.

For those steels (principally the chromium irons and the stainless steels) which, because of the nature and quantity of the alloying elements present, are difficult to scarf, the iron-powder process has been used with some success. As in the case of oxygen cutting, the alloying elements responsible for the corrosion-resistant properties of these materials effec-

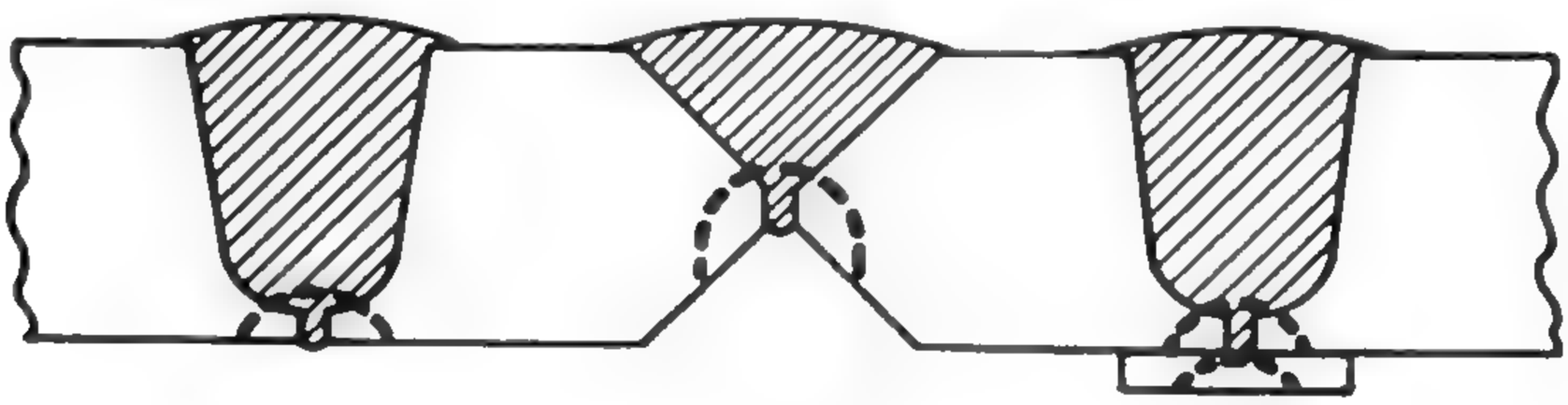

Fig. 6.—Gouging Operations on Arc Welds

The balance of the equipment for manual gouging and scarfing is identical with that employed in cutting operations. Hose of adequate size to provide gas capacity of sufficient volume to handle the heavy gas flows should be used, and unnecessary restrictions in the line should be avoided. The regulators are also identical with those used in cutting operations. Regulators should be of sufficient capacity to admit the required gas volume and so prevent starving of the tips. The gas supply should either be from manifolded cylinders large enough to furnish the volume of gas required or from a pipe line adequate in size for the amount of scarfing being done and for supplying other gas loads that may be imposed simultaneously on the lines.

The most important piece of auxiliary equipment used in conjunction with the scarfing torch is the starting rod feed device. This consists of an assembly of mechanical linkages operated by a lever located beneath the handle of the torch

tively hinder the action of the oxygen stream in the scarfing operation. However, results using the iron-powder process indicate that scarfing of these materials can be successfully accomplished. The same type of iron-powder hopper or dispenser described in Chapter 24 for oxygen cutting of these materials may be used for scarfing. A special scarfing torch and tip designed to convey the iron powder to the reaction zone, as well as the preheat gases and the scarfing oxygen are required. In other respects the additional equipment required is similar to that used for cutting by the iron-powder method. The essential difference is mainly in the proper design of the torch and tip for application to the scarfing processes.

Mechanical Scarfing and Grooving

Mechanical scarfing equipment can be classified in two different categories.

The first type is that used by steel mills for scarfing billets or bars to remove surface defects prior to the subsequent rolling

operations. These machines are often inserted permanently or retractably in the roll line, and become one of the component pieces of equipment in the steel mill's production line. However, as this equipment is of a specialized nature, and is built and engineered to meet special customer specifications, it will only be briefly considered. Such equipment constitutes a major capital investment, and its use is practical only on a production basis. Extensive study of the economic factors involved is essential for each contemplated installation.

Billet scarfing, or desurfacing machines, as they are usually called, have been built for either hot- or cold-scarfing applications. Some machines scarf one surface of a billet at a time, making it necessary to turn the billet and make successive passes if the entire billet is to be scarfed. The more modern machines, those built for use as a component part of the roll line of a steel mill, are capable of scarfing the four sides of a billet simultaneously. Essentially automatic in operation, these machines are manipulated by an operator from a pulpit having push button controls. Positioning of the scarfing tips is usually accomplished by hydraulic power, while the gas supply is actuated by solenoid valves, all under the operator's direction.

The second type of equipment is used for plate edge preparation for welding. For such applications mechanical holding and guiding of the torch and tip are required. A movable carriage type of machine mounting a standard cutting torch, as described in Chapter 24, is ideally suited for this work. As this equipment is exactly similar to that used for oxygen cutting, further description is not necessary.

Other Oxygen-Machining Processes

As previously indicated surface planing, oxygen turning, etc., employ the same equipment as scarfing, gouging and cutting modified for the particular application.

COMMON APPLICATIONS

Manual Scarfing and Gouging

Manual scarfing (deseaming) and gouging are essentially similar processes, the principal difference being that the degree of accuracy of metal removal with a gouging torch is considerably greater than that with a scarfing or deseaming torch. In conditioning steel billets and slabs by scarfing or deseaming the primary object is to remove a wide, shallow layer of metal, thus eliminating surface defects and leaving the resulting surface prepared for subsequent rolling operations. Gouging, with its characteristic U-shaped contour, removes the metal to a depth below the surface or shapes an edge in such a way as to prepare a groove properly shaped for welding operations.

Scarfing

Scarfing, or deseaming, covers those operations of surface conditioning of steel blooms, slabs, and billets preparatory to finish rolling in the steel mill. It has to a large extent replaced chipping with the pneumatic chisel for the removal of cracks, seams, scabs, and crows feet from steel stock to avoid surface imperfections in the finished product.

Scarfing has decided advantages over chipping as a means of removal of these defects. It is many times faster than chipping and shows up cracks which other methods of surface conditioning might not. It also results in reduced floor space requirements for steel conditioning operations. Scarfing makes it possible to salvage many steel stocks too badly checked to warrant chipping. Contrary to supposition scarfing does not cover up defects, but actually exposes small cracks and imperfections.

An important application of hot, manual scarfing is the removal of tears and scabs in forging operations whereby the need for cooling and reheating incident to chiping operations is eliminated.

Gouging

Gouging is used extensively to remove defects in steel revealed by radiographic, magnetic particle, supersonic or other inspection methods. Other applications include the removal of tack welds or defective welds, and defects in steel castings due to blowholes or sand inclusions. It is also used in demolition work, in removing welds from temporary brackets or supports, for removing flanges from piping, heads from boilers, and for removing old tubes from boilers by gouging the tubes internally where they enter the head sheet of the boiler, prior to collapsing them. It is also used in preparing plate edges for welding.

Manual gouging is a fast method of metal removal, speeds from 1 to 3 lineal ft. per. min. being obtained. Depending upon the skill of the operator, it is possible to control the accuracy of the gouge formed within a tolerance of about $^{1}/_{16}$ in. in both width and depth. The equipment is readily portable so that it can be used for the removal of defects which might otherwise be inaccessible. The process is relatively quiet and maintenance costs are less than for mechanical processes which require repeated sharpening of tools.

Mechanical Scarfing and Gouging

Some of the early machines were built to mount a battery of scarfing torches and were so constructed that the machine traveled on rails alongside the work and carried the scarfing torches over the surface at the required height and at the proper angle. This type of machine is still used today to a limited extent, but it has been largely supplanted by the stationary-type machine mounted directly in the roll line of the steel mill. For the fixed-position machine the work at approximately rolling temperature is moved through the machine by driven supporting rolls and guided by idler and pinch rolls as needed.

Fixed-position scarfing machines are used today mainly for scarfing blooms and billets with cross-sections of 4 to 14 in. on a side, or rectangles. Surface removal of slabs 76-in. wide to a depth of $^{1}/_{8}$ in. on all four sides simultaneously is possible at speeds in excess of 125 linear ft. per minute. Shallower removal can be done at speeds between two and three times this figure.

The stationary-type scarfing machines are built so they can be retracted, or lifted, from the roll line with idler rolls substituted to permit repairs and maintenance on the machine without interrupting the schedule of the mill. The scarfing head of the machine is constructed in segments, allowing each to be moved into position, and adjusted by hydraulic or pneumatic controls for blooms of various sizes. Each segment is free to float in a direction perpendicular to the axis of the bloom. The segments of the scarfing head mount the water-cooled scarfing tips, or tip segments, which must be water cooled. The gases fed to the tips are controlled by individual shut-off valves. The entire machine is handled by the controls which are located in a pulpit near the rolling line in a position giving good visibility for the operation.

Other considerations are the provision of adequate facilities for handling the large volume of slag and fumes produced during the scarfing process. Special slag pits equipped with water sprays to break up the slag and flush it away to a settling pit are provided, as well as a fume hood and exhaust fans connected to a conveniently located stack.

In mechanical scarfing the oxygen consumptions are extremely high. For an installation capable of handling 200 tons of steel per hr., some six tons of surface may be removed resulting in about 10 tons of fumes and slag, and requiring approximately 20,000 cu. ft. of oxygen, and about 1000 to 3000 cu. ft. of acetylene. Short-duty cycles for these machines result in momentary oxygen demands which may exceed 150,000 cu. ft. per hr. and the oxygen supply and gas-handling equipment must be engineered to supply these demands.

The oxygen consumption in terms of the weight of metal removed depends on various factors, including the depth of scarf, carbon content and analysis of the steel, and the temperature of the steel. For cold scarfing, a rough figure for the oxygen consumption is between 2.0 to 3.5 cu. ft. per. lb. of metal, while for hot scarfing in the vicinity of 2000°F., this index is in the neighborhood of 1.0 to 1.3 cu. ft. of oxygen per lb. of metal removed. It is interesting to note that in cold scarfing a large percentage of the metal removed is oxidized, while in hot scarfing the resulting slag contains an exceptionally high iron content. The slag obtained from hot scarfing operations has been found to contain as much as 88% iron, indicating that a melting action is predominant. This would also account in part for the fact that alloy steels may often be scarfed hot, when at ordinary temperatures they cannot be scarfed satisfactorily.

Hogging

Hogging is an increasingly important foundry process used for removing superfluous metal from steel castings. It includes the removal of risers and sprues which are often of such a nature or so located that it is difficult or impossible

to remove them by ordinary oxygen-cutting methods. Hogging cuts are very similar in cross section to those illustrated in Fig. 5. The depth of the cut, however, may be considerably greater when required. Such deep cuts are sometimes characterized by rough surfaces, but subsequent oxygen planing will provide a satisfactory finish.

Planing

Gang assembly of planing tips or nozzles has been used for certain types of hogging cuts. These cuts, however, are more typical of surface planing. In this operation cuts are made in parallel relation-

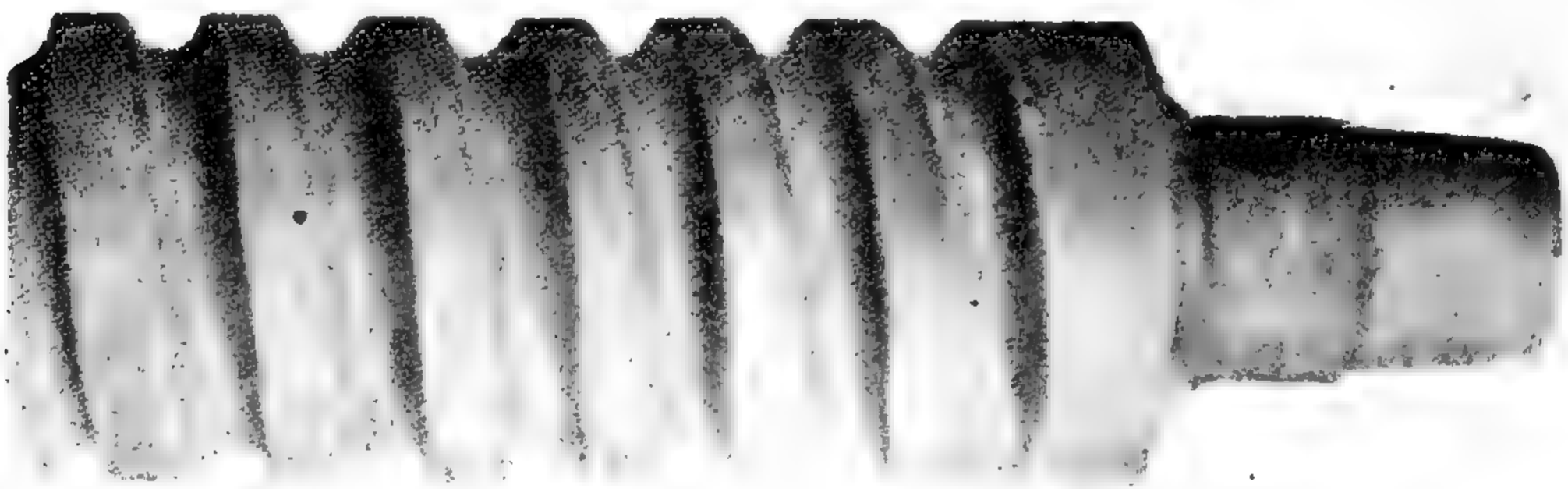

Fig. 7.—Oxygen Machined Coarse Pitch Screw

ship, permitting the removal of wide surfaces (Fig. 5, *c* to *g*). When performed mechanically, close dimensional allowances on depth and width of the individual cuts may be maintained so that the resulting surfaces are at least equal to those formed by rough surface tool planing. Control of surface regularity is dependent on the selection of the proper profile style and on the careful spacing of the cutting tips.

Oxygen Turning

Turning operations are similar to the planing operations just described, although this process is so recent that few commercial applications have as yet been made.

Material Which Can Be Oxygen Machined

Oxygen machining (gouging, planing, milling, etc.) is usually carried out on low-carbon and mild steels, and no difficulties are experienced due to the analyses of these materials. As a general rule, the remarks included in Chapter 24 on material which may be readily cut apply equally to the oxygen machining processes. For this reason they will not be repeated here, except in brief outline.

For high-carbon and low-alloy steels, care must be exercised in deciding whether the application and the material to be oxygen machined will give the desired results without encountering objectionable effects, such as hardening, cracking and checking. However, by the proper application of preheat many of the SAE series steels may be oxygen machined successfully. Included in such a list are the free-cutting manganese, nickel, nickel-chromium, molybdenum and silicon-manganese steels, especially in the lower alloy ranges. It is impossible to indicate definitely whether a particular application involving these steels will be successful since there are no arbitrary limits to the analyses which may be oxygen machined, and because with many variables present it is often possible to vary them appropriately to obtain acceptable oxygen-machined surfaces.

Certain steels, notably the stainless steels having high chromium and nickel content, are not readily scarfed. In recent years, flux-oxygen cutting has been used for scarfing stainless steels. (See Chapter 24).

Fields or Industries in Which Commonly Used

The steel industry finds major use for the oxygen machining processes. Since their introduction, the processes (predomi-

nantly the scarfing process) have been used extensively to replace the chipping hammer to a large extent. Because of more stringent buyer specifications dealing with the surface finish, mechanical scarfing of large tonnages is being performed today with the expectation that in the future an even greater percentage of the total tonnage produced will be scarfed steel.

Other industries, such as the shipyards and railroads, find use for these processes for plate edge preparation and the removal of defects in welding and castings. Both these industries use gouging for the correction of spot defects and both make use of the cutting torch for rivet washing for the removal of damaged riveted steel plates requiring replacement.

Fabrication shops have, to a limited extent, used oxygen machining for making initial cuts on large pieces of equipment. Depending on the surface requirements, the cut produced by oxygen machining may or may not be satisfactory for use as produced. Typical examples of this type of work are shown in Figs. 7 and 8. However, the use of the processes is still in its infancy and there is room for great improvement.

Salvage industries have already been mentioned as users of these processes. Manual gouging and rivet washing are the two processes mainly used in salvage work. Other principal users of oxygen machining include foundries, which by removing riser pads eliminate to a large extent costly swing grinding.

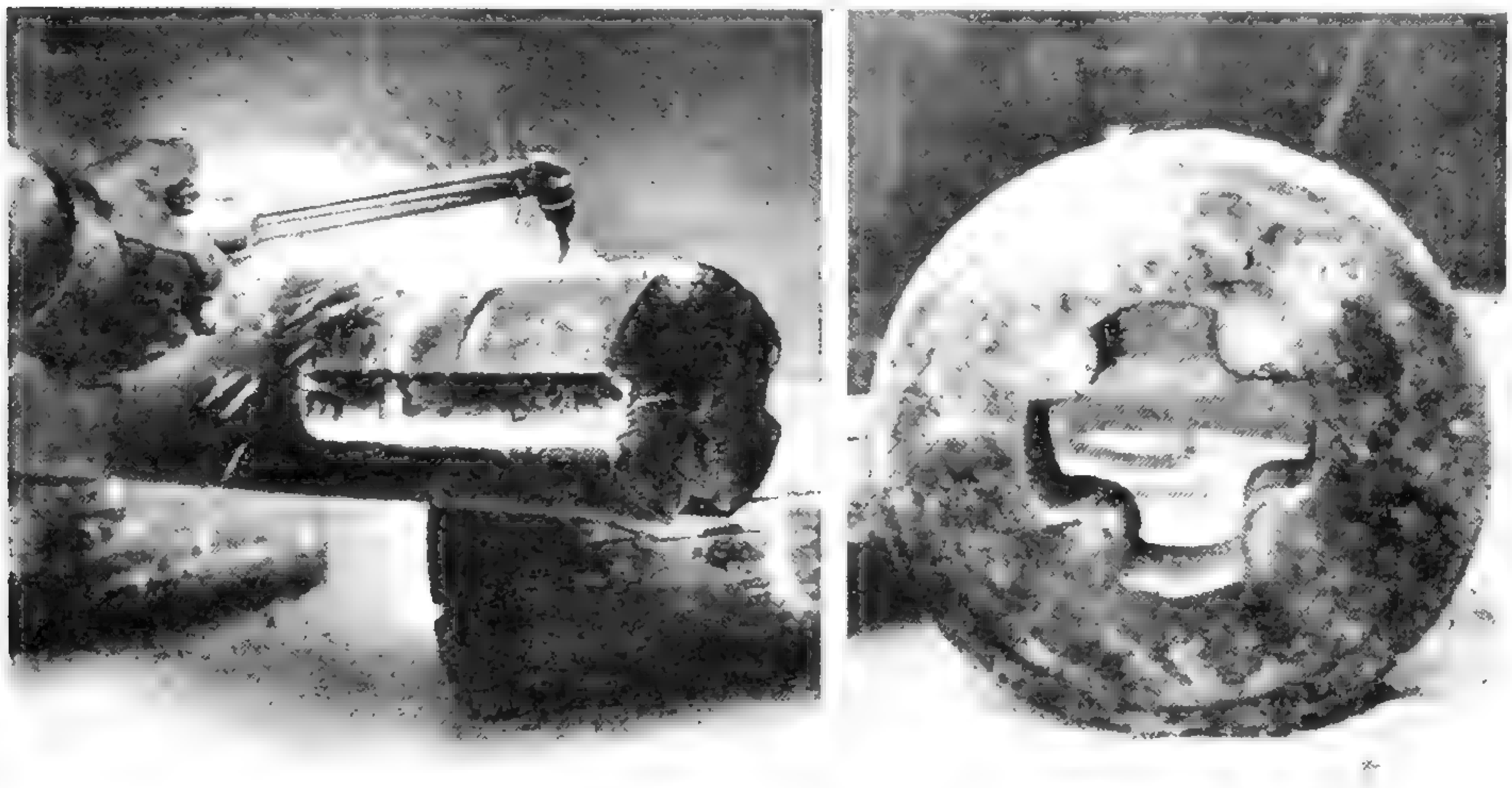

Fig. 8.—Gouging an 8-In. Shaft to Fit Rolling Mill Drive Clutch

BIBLIOGRAPHY

1. *Machining with Oxy-Acetylene*, H. H. Moss, American Machinist, December 31, 1932 and January 4, 1933.
2. *Conditioning, Shaping and Machining of Carbon Steel by Oxygen*, H. H. Moss, The Welding Journal, January 1933.
3. *Machine Cutting and Flame Machining by the Oxyacetylene Process*, R. F. Helmkamp, The Welding Journal, February 1934.
4. *Plate Edge Preparation for Welding*, H. E. Rockefeller, The Welding Journal, January 1940.
5. *Steel Conditioning with the Oxy-Acetylene Method*, G. D. Winlack, Iron and Steel Engineer, April 1940.
6. *Flame Scarfing Billets*, John Heffley, Steel, July 15, 1940.
7. *Scarfing Billets and Slabs*, Steel, November 11, 1940.
8. *Flame Machining, Control and Applications*, G. L. Walker and W. G. Sylvester, The Welding Journal, February 1941.
9. *Hot Scarfing of Billets, Blooms and Slabs*, E. A. Doyle, Iron and Steel Engineer, May 1941.
10. *Scarfing High Carbon and Alloy Steels*, C. D. Winlack, Iron and Steel Engineer, April 1942.
11. *Billet Preparation for Rolling Mills*, F. F. Cambert, Iron and Steel Engineer, June 1945.
12. *Flame Deseaming*, Fred Judelsohn, Iron and Steel Engineer, December 1947.

CHAPTER 26B

FLAME HEATING AND HEAT TREATING*

FUNDAMENTALS OF PROCESSES

Definitions and General Description

THE PROCESSES covered in this section include flame hardening, flame softening, flame strengthening, flame cleaning, flame straightening and flame shrinking.

Flame hardening is the heating of the surface layer of an iron-base alloy above the transformation temperature range by means of a high-temperature flame and then quenching.

Flame softening is the tempering or annealing of iron-base alloys which have previously been hardened in the course of cutting, or other working, by heating to suitable temperature ranges with an oxy-acetylene flame and slow cooling.

Flame strengthening is the use of an oxy-acetylene flame to heat treat local areas, which will be highly stressed in service, to increase their tensile strength.

Flame cleaning is the use of an oxy-acetylene flame for removing scale, rust, dirt and moisture from steel surfaces preparatory to painting.

Flame straightening is the use of an oxy-acetylene flame to heat steel parts and correct distortion. The process is often used prior to or after welding.

Flame shrinking is the use of an oxy-acetylene flame to heat a steel part to a plastic state following which it is shortened by mechanical means.

For the sake of clarity each of the foregoing processes is discussed separately.

FLAME HARDENING

Principles of Operation

The flame-hardening process employs the heat of an oxy-fuel gas flame to produce a relatively shallow heated zone in a ferrous material such that subsequent quenching with suitable media, generally water, compressed air or a soluble oil, will increase its surface hardness. The main difference between furnace hardening and flame hardening is that in the former process the entire object must be brought to hardening temperature, whereas in the latter, only a thin surface layer, about $^1/_{16}$ to $^1/_8$ in. in thickness, or a localized area is so treated. Since flame hardening has been applied to hardening thin surface layers of thicker sections, it has been loosely termed *local hardening* or *surface hardening,* and has been confused with the carburizing process of case hardening and with nitriding.

Flame hardening employs the flame merely as a heating medium and involves no change in the chemical composition of the material such as the introduction of carbon or nitrogen into the surface layers of the material, as in case hardening. Because of the rapid rate of heating and the sharp temperature gradient between the surface and the interior of the object, a substantial self-quenching effect is obtained which in some cases is sufficient to produce the desired surface hardness by air cooling.

The principles of operation of flame hardening are no different from those of furnace hardening. For an understanding of the changes a steel undergoes in a hardening operation, a knowledge of metallurgy is required, and in this connection the reader is referred to Chapter 3.

Hardening Techniques

Flame hardening can be accomplished either manually or mechanically.

Spot Hardening.—Where limited areas of a part are to be treated, the area can be heated above the critical temperature by manually manipulating the torch back

* Prepared by a committee consisting of S. T. Walter, Air Reduction Sales Co., *Chairman;* R. L. Deily, Arcway Equipment Co.; H. V. Inskeep, The Linde Air Products Co.; Bela Ronay, U.S. Naval Engineering Experiment Station; C. M. Underwood, Northern Ordnance, Inc.

and forth across the surface. The torch is then removed and the surface quenched with water, compressed air, or immersed in oil as required by the particular composition of the material. Extensive use is made of this method in hardening rail ends to reduce batter.

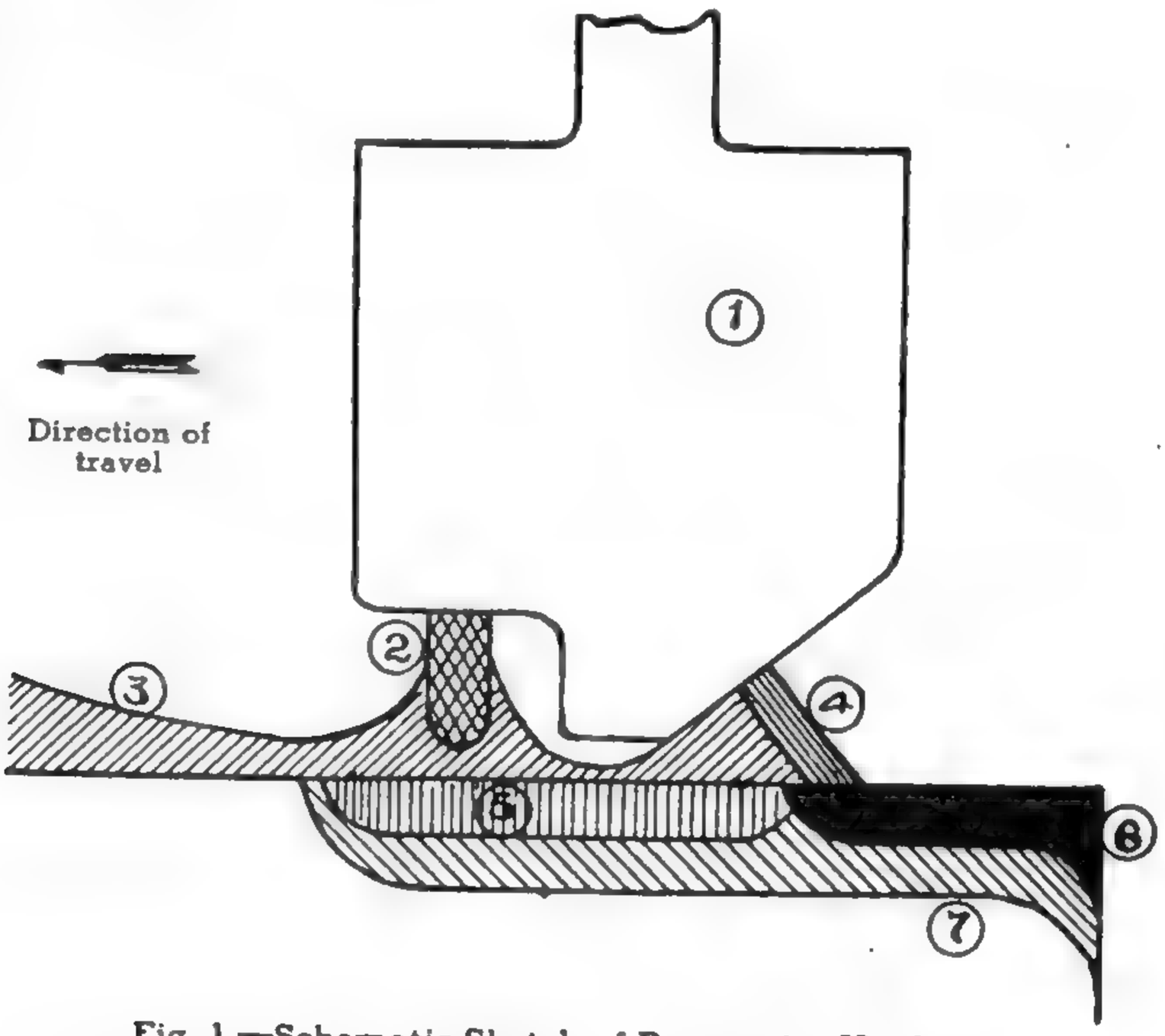

Fig. 1.—Schematic Sketch of Progressive Hardening

1, Torch; *2*, Inner Cone; *3*, Outer Flame; *4*, Quenching Jet; *5*, Metal Heated Above Critical Temperature; *6*, Hardened Zone; *7*, Annealed Zone.

Progressive Hardening.—In hardening extended areas, the process is made continuous by incorporating both heating and quenching functions in the hardening tip or burner, and providing means for moving either the work or the equipment at a constant speed along the path to be hardened. Heating is accomplished by one or more rows of small flames followed closely by a row of quenching jets. This method results in a more severe self-quenching effect than occurs where the entire surface to be hardened is simultaneously heated to the hardening temperature. A water quench unless carefully applied is generally too severe for the higher carbon steels and compressed air or compressed air-water mixtures are used.

Figure 1 illustrates in schematic form the method of progressive hardening. The tip progressively heats the surface along the path of travel to hardening temperature and the quenching stream following imparts a uniform hardness to the area covered. The speed of travel will vary from 3 to 12 in. per min. depending on the size and number of flame ports (heating orifices), and determines the penetration of the hardness. The degree of hardness obtained for a given steel analysis is regulated by the temperature to which the surface is heated and by the nature and volume of the quenching stream. For example, for 0.30% carbon steel the hardening temperature would have to be around 1530°F. (the A_3 temperature is about 1487°F. for such a steel). For a higher carbon steel, the hardening temperature is lower. A 0.70% carbon steel would require a hardening temperature in the vicinity of 1430°F. (the A_3 temperature in this case is about 1367°F.).

Hardening Cylindrical Surfaces.—Cylindrical surfaces, both external and internal, can be successfully flame hardened. Three different methods are in common use, the choice depending on the length and diameter of the cylindrical object.

1. *Spinning Method.*—Narrow bands of surface can be flame hardened on cylindrical surfaces of small diameter,

such as crankshaft journals, by spinning at surface speeds of about 1000 lineal in. per min. under a heating tip or burner. The heating tip should be of sufficient size to cover the width of surface to be hardened. When the entire surface to be hardened has been raised to the hardening temperature, the heating flames are extinguished and a quenching stream applied to the spinning surface. with the cylinder rotating with a surface speed of about 1000 lineal in. per minute. Heating heads and quenching jets are often mounted on a lathe tool post. One or more heating tips or burners, depending upon the diameter of the object, are spaced at equal intervals around the object perimeter, so as to heat a narrow band to the hardening temperature. An advantage of the progressive spinning

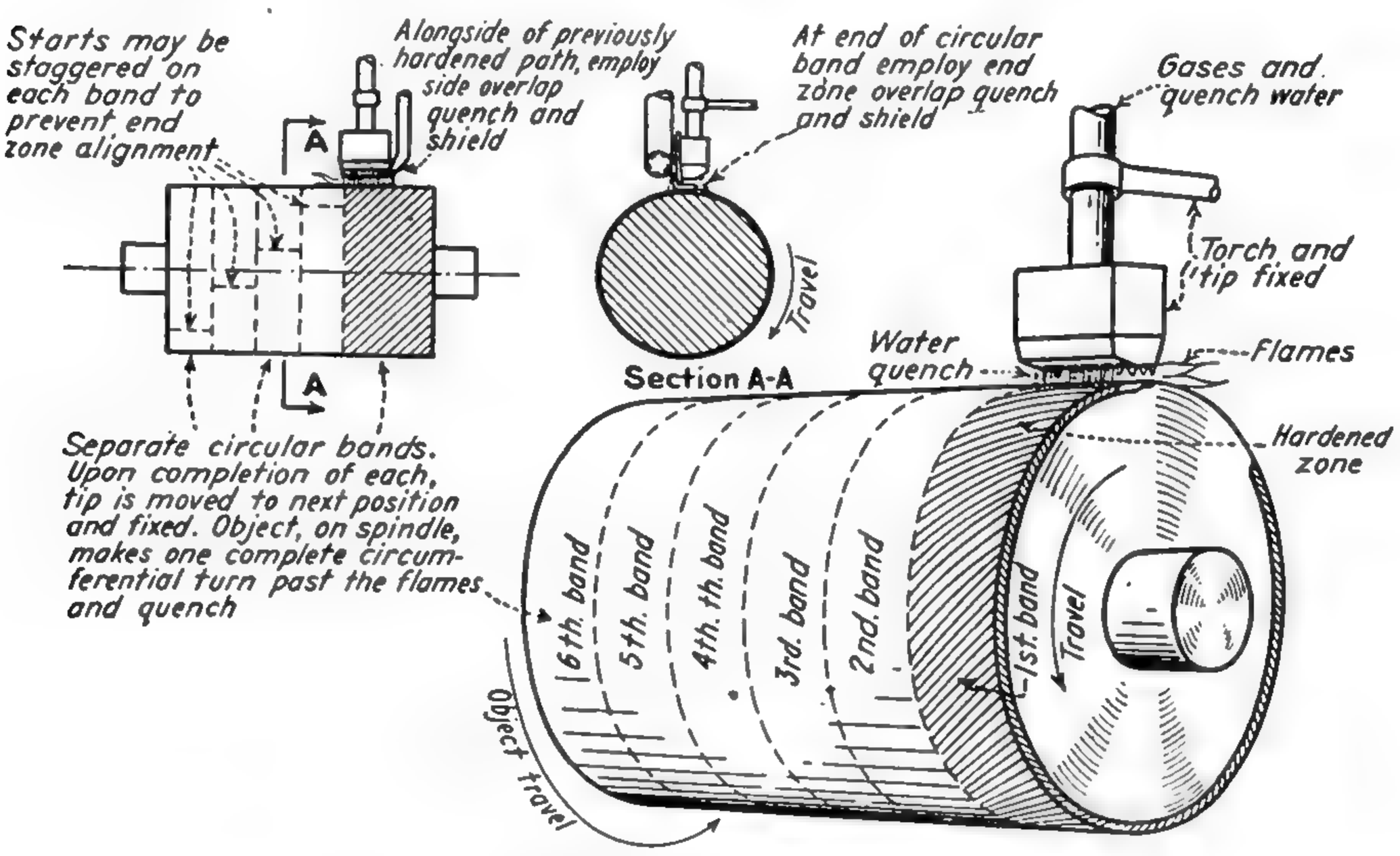

Fig. 2.—Hardening by Progressive Cylindrical Method

Larger diameter surfaces may require two or more such heating tips or burners equally spaced around the cylinder circumference to increase the speed of heating or to reduce the depth of penetration. The spinning method is the simplest for hardening cylindrical surfaces and should always be considered where the size and shape of the object to be hardened permit. Since the entire surface to be hardened is raised to the hardening temperature at the same time, the flame adjustment, torch positioning and the nature and degree of quenching are not critical. In addition, the temperature of the heated surface can be accurately observed before applying the quench.

2. *Progressive Spinning Method.*—Cylindrical surfaces of extended length can be hardened by progressively heating a spiral band $^1/_2$ to 1-in. wide, followed axially at a distance of $^1/_4$ to $^1/_2$ in. by a quenching stream, along the axis of the cylinder at a rate of 3 to 12 in. per min., method, aside from making possible the hardening of cylinders of extended length, is that much of this type of hardening can be done with standard oxy-acetylene welding equipment which is generally available .

3. *Progressive Cylindrical Method.*—This is an adaptation of the progressive hardening method previously described. It differs from the progressive spinning method in that the object is rotated at a much slower speed and circular surface bands are hardened. This usual peripheral speed is between 3 to 12 in. per min., 6 in. per min. being most common. To prevent drawing the hardness at the overlap of adjacent areas an auxiliary cooling stream is sometimes used ahead of the hardening tip (see Fig. 2). Because of the possibility of developing surface checking by passing the flame over an already hardened area, it is common practice to avoid overlapping the heating passes. The narrow band of

lower hardness, between the passes, is generally not objectionable on broad bearing surfaces.

Miscellaneous Procedures. — Flame-hardening tips can be designed to fit irregular contours such as cam surfaces or lathe spindle noses and gear teeth. In many cases, however, it is preferable to split up such a contour into several parts and harden each part of the contour as a separate operation. The resulting simplifications in tip design considerably reduce their cost and promote easy operation. In hardening gear teeth, the tooth profile may be divided into two parts and heating tips are designed to fit each half of the tooth contour. Spur, sprocket, worm and herringbone gears are hardened by mounting the tips or burners in a yoke at a fixed distance apart and providing for uniform motion of the tips or burners along the tooth.

Special equipment is required in the case of worm and herringbone gears to rotate the gears as the tips or burners move in a straight line along the gear axis, and with bevel gears for varying the spacing of the hardening tips and the speed of the torch travel to accommodate the varying cross-section of the tooth. Gear hardening machines, incorporating these features, are made by several companies manufacturing gear-cutting equipment.

Materials

Steels.— Any type of hardenable steel, including stainless, can be flame hardened if the proper procedures are followed. The carbon content should be 0.35% or more for appreciable hardening. The best range for most flame hardening methods is 0.40 to 0.50%. The alloy content will determine the type of quench to be used. Straight carbon steels in the range indicated can usually be given a rapid quench. The quench for alloy steels can be varied from a rapid quench to air cooling, depending upon the hardenability of the steel. Sometimes a quench using compressed air immediately behind the flames is followed by a quench using water. Full hardness cannot always be expected with the slower cooling rates. Typical hardness patterns in a flame-hardened steel shaft and in a gear tooth are shown in Figs. 3 and 4, respectively. Figure 3A shows a shaft with a hardened

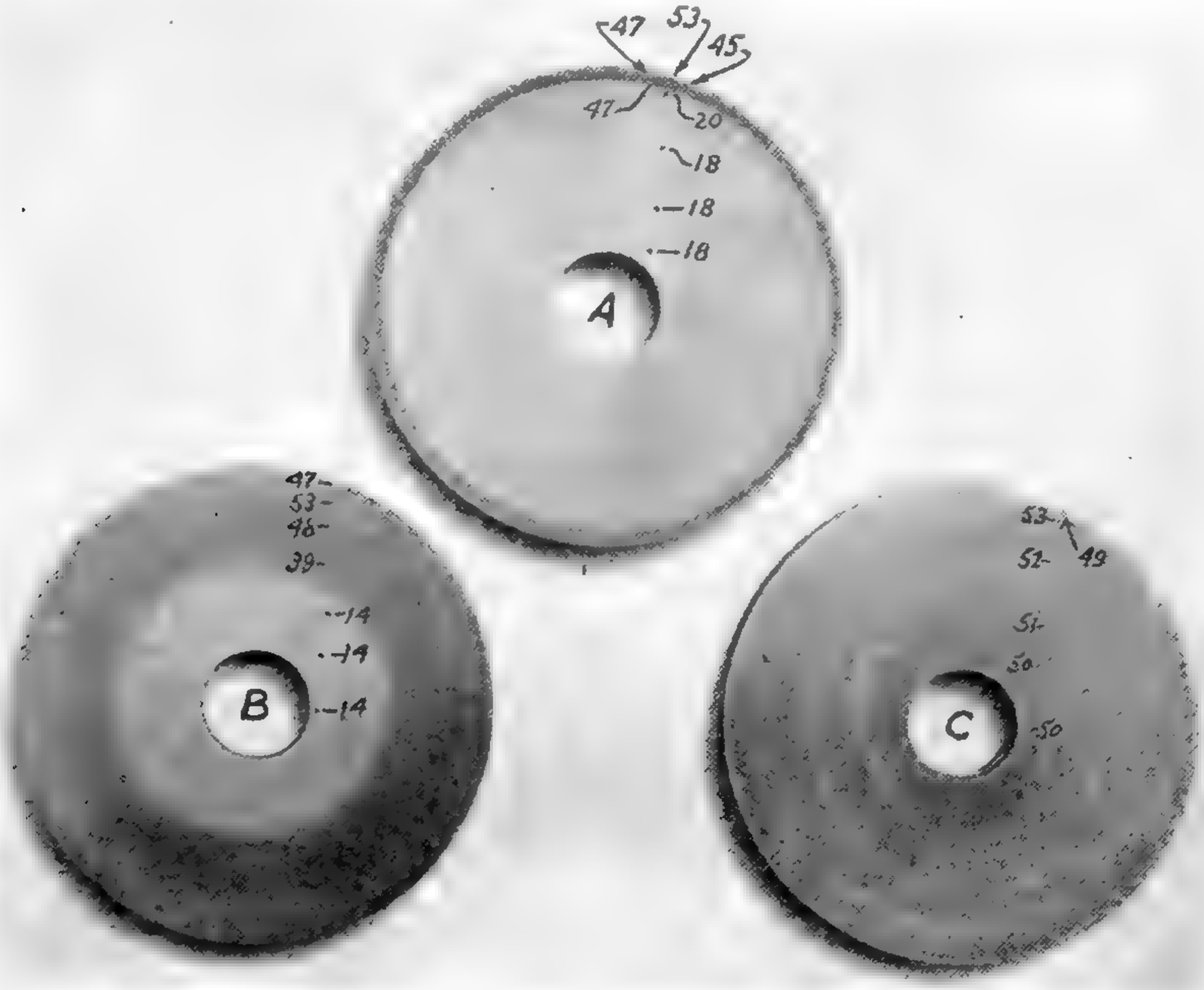

Fig. 3.—Hardness Patterns Obtained in a Flame-Hardened Steel Shaft

case $^1/_8$-in. deep, Fig. 3B shows a shaft hardened halfway through and Fig. 3C shows a shaft hardened throughout its thickness. The hardness values shown in Figs. 3 and 4 are Rockwell C.

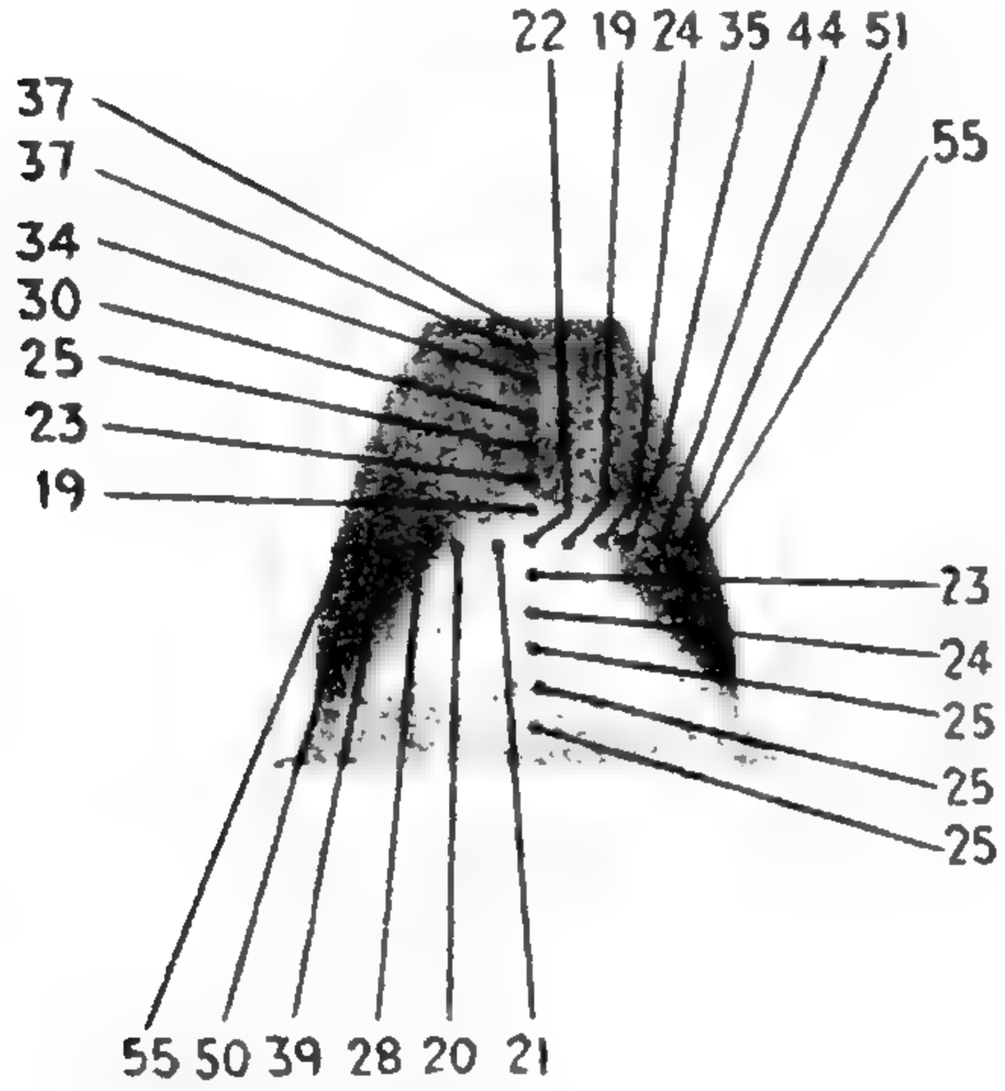

Fig. 4.—Hardness Pattern Obtained in a Flame-Hardened SAE 4640 Gear Tooth

Cast Iron.—Pearlitic cast irons offer a broad field for the flame hardening process. Chilled cast iron has high resistance to wear, but chilled castings cannot be machined. Pearlitic cast iron can be machined to dimension and then flame hardened, greatly increasing the resistance to wear. In general, gray cast iron should have about 0.40 to 0.80% combined carbon for satisfactory hardening. Alloying elements such as nickel, chromium, molybdenum and vanadium, in the amounts used in cast iron, have little effect on the results. Cast iron is easily overheated and in general should be hardened at lower temperatures than steel. Any specific cast iron should be tested for hardenability, since poor results can be obtained even though the chemical composition may be correct.

Physical Properties of Flame-Hardened Parts

Tables 1 to 4 give some cast iron and steel types which are successfully flame hardened, and contain data on the metallographic and mechanical properties obtained by flame hardening. Tables 1 and 2 contain data relative to the surface hardness produced on representative steels and cast irons, using water or compressed air quenches. Since these data were taken under varying conditions of heating and quenching on objects of various sizes and shapes, they do not represent the maximum hardness obtainable for the various analyses. Table 3 illustrates the mechanical properties obtainable in flame-hardened surfaces. Table 4 indicates the structure produced by flame hardening at varying depths below the surface. A very gradual transition in hardness from the martensitic surface to the pearlitic core is obtained in flame hardening.

Figure 5 indicates the relation of Vickers Hardness and depth of case in a typical flame-hardened steel part.

Heat Treatment of Flame-Hardened Parts

Large forgings and castings are normalized, annealed and stress relieved to improve the grain structure and reduce stresses which might cause distortion. High-quality gears are commonly furnace hardened to 250–300 Brinell to obtain the necessary strength in the core. Flame hardening the contact surfaces of the gear teeth to 400 Brinell or harder does not affect the tensile strength of the core except in a very shallow tempered zone under the flame-hardened area.

Postheat treatment should be applied to parts which are subjected to high impact stresses in service to reduce stresses produced by flame hardening. Such heat treatment generally consists of drawing or stabilizing at 350 to 500°F. It has been found that in this temperature range, a considerable improvement in fatigue and shock resistance is obtained with very slight reduction in indicated hardness. The immediate application of a draw treatment may also prevent hardening checks or cracks when such defects are likely to occur.

Distortion

The amount of distortion encountered in flame hardening is usually of minor extent; in many instances, it is within usual manufacturing tolerances.

There are two main effects which may produce distortion in a flame-hardened part. First, where progressive heating is used, the heated zone surrounded by a rigid cold mass of metal tends to upset, resulting in distortion of the part upon quenching. Secondly, due to the change

Table 1—Observed Flame Hardness of Various Steels

SAE Number	Percentage Composition C	Mn	Cr	Other Elements[a]	Brinell Hardness Compressed Air Quench	Water Quench
..	0.35	1.45	...	....	...	500
1040	0.35	0.80	...	....	...	444
1045	0.45	0.75	...	....	...	555
1055	0.55	0.74	...	....	...	712
1095	1.00	0.30	...	.....	...	700[b]
51210	0.12	Forging Rolled Stock	13.00	....	444	444
3140	0.40	0.80	0.60	1.25 Ni	...	540
2330	0.30	0.68	...	3.48 Ni	...	600
4140	0.40	0.80	0.95	0.20 Mo	375	525
	0.68	0.75	...	0.34 Mo	...	712
	0.90	..	...	0.25 V	...	725
6140	0.40	0.75	0.95	0.17 V	500	...

[a] Amount of P, S and Si typical of grade.
[b] Mild quench.

Table 2—Observed Flame Hardness of Cast Irons

Type of Iron	Percentage Composition Total C	Combined C	Si	Mn	P	S	Ni	Cr	Mo	Brinell Hardness Water Quench
Gray	3.46	0.76	1.58	0.76	0.144	0.083	..	...	..	540–600
Gray	3.44	0.69	1.51	0.87	0.194	0.087	..	...	..	550–610
Gray	3.44	0.77	1.70	0.75	0.300	0.085	..	...	..	550–615
Meehanite A	2.97	0.66	1.62	0.78	...	...	Nil	0.045	..	500–605
Meehanite C	3.04	0.68	1.65	0.79	...	...	Nil	0.045	..	500–620
Gray	3.22	0.65	1.73	0.75	0.212	0.089	..	...	0.47	560–635
Gray	3.15	0.70	2.00	0.90	...	...	1.37	...	..	525–575
Gray	3.30	0.73	1.34	..	...	...	1.43	...	0.85	550–605
Gray	3.19	0.84	1.22	..	...	...	1.11	0.10	0.76	550–605
Gray	2.87	0.84	1.87	..	...	...	0.18	0.21	..	560–610

Table 3—Typical Composite Properties of Flame-Hardened Pretreated Steels

	Percentage Composition				
C	0.34	0.33	0.42	0.43	0.35
Mn	0.61	0.62	0.83	0.57	0.68
Cr	..	0.64	..	..	0.93
Ni	1.75	1.52	..	3.60	..
Mo	0.25	..	..	..	0.21
	Core Properties				
Tensile, psi.	185,000	130,000	105,000	135,000	180,000
Elastic limit, psi.	175,000	110,000	75,000	125,000	160,000
Izod, ft. lbs.	35	75	27	69	65
	Surface Hardness				
Brinell	555	534	514	578	627

Table 4—Hardness and Constitution of Flame-Hardened Surfaces

Type of Steel	Percentage Composition C	Mn	Ni	Cr	Mo	Brinell Hardness	Nature of Hardened Surface Total Depth Affected, In.	Depth of Martensite	Depth of Troostite, etc.
SAE 1050	0.46	0.69	..	..	..	615	0.130	0.078	0.052
SAE 5140	0.42	0.71	..	1.05	..	615	0.108	0.084	0.024
Mn-Mo	0.39	1.59	..	..	0.31	610	0.111	0.092	0.019
SAE 3230	0.29	0.56	1.52	1.16	..	610	0.108	0.080	0.028
SAE 4340	0.30	0.60	..	1.13	0.31	592	0.108	0.096	0.012
SAE 2340	0.36	0.70	3.34	0.20	..	585	0.123	0.086	0.037
Ni-Cr-Mo	0.32	0.56	2.56	0.72	0.42	555	0.134	0.120	0.014

in phase of the steel, a slight change in volume of the hardened steel occurs, again causing the piece to distort. The first effect tends to shorten the heated side, while the second tends to lengthen it somewhat. It is difficult to estimate these distortional factors for various steels and no general rule for predetermining the extent of distortion can be given.

distortion on test specimens has been reduced 25 to 40% with little reduction in hardness. However, such treatment is time consuming. Occasionally, under well controlled conditions as by carefully controlling the quench in application, quantity and timing, the flame-hardening operation may be made to act in the final stages as a self-tempering treatment.

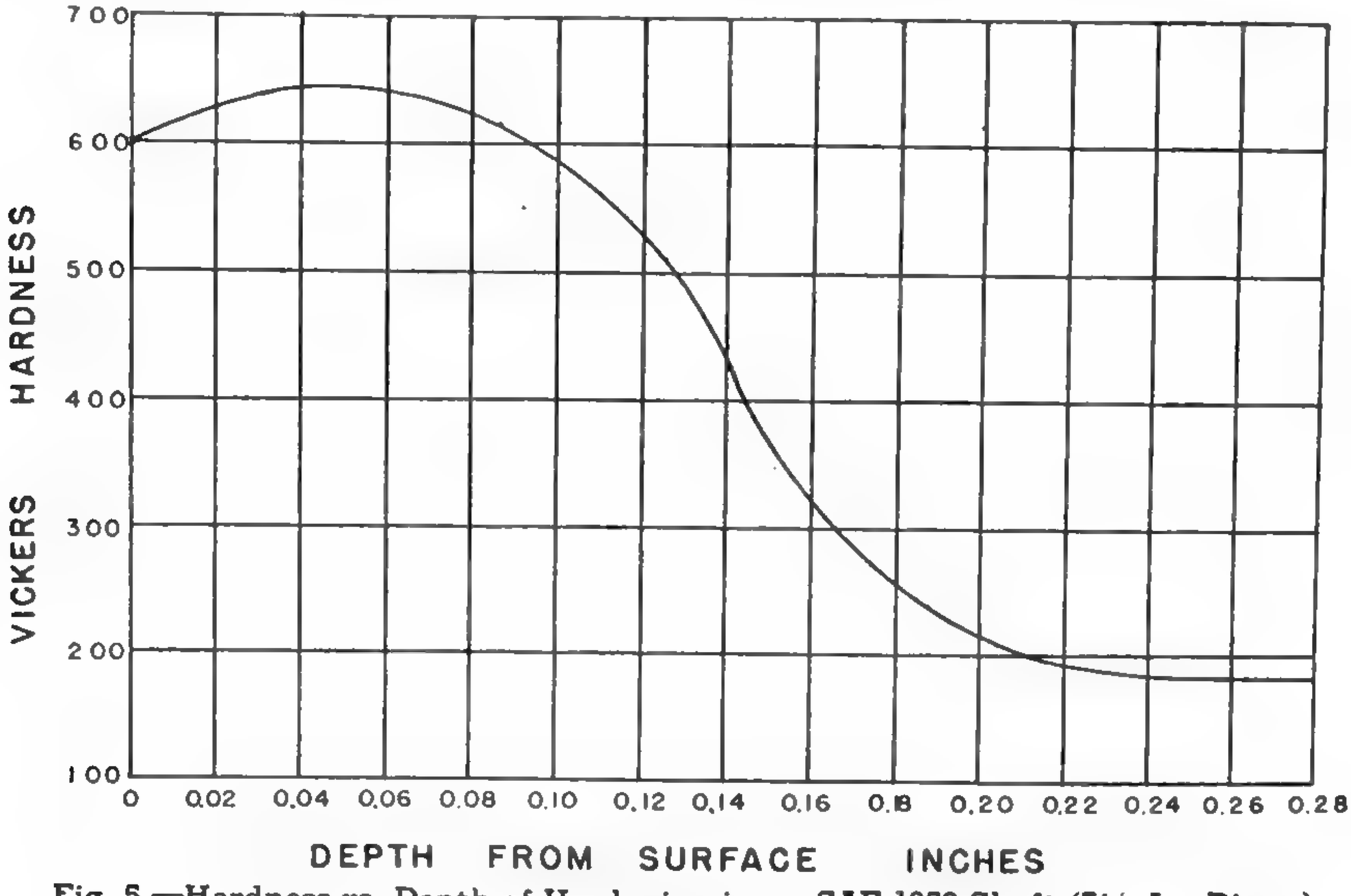

Fig. 5.—Hardness vs. Depth of Hardening in an SAE 1050 Shaft (7½-In. Diam.)

Other factors which influence the incidence of distortion of a flame-hardened object to a minor degree include the analysis of the material used, the thickness of the material, the depth of hardness, the rate of quenching, and the design of the part.

Furthermore, most cast and rolled materials contain internal stresses, which upon heating will be partially relieved, resulting in warpage or distortion of the part. Difficulty from this source may usually be overcome by fully annealing before hardening to dissipate existing stresses.

Distortion may be controlled to some extent by various expedients such as partially immersing the object in water, or by compensating for the expected distortion by prebending in the reverse direction before hardening.

When distortion does occur it is possible in many cases to reduce its severity by a stress-relief drawing treatment (tempering). Instances have been reported when

On small parts it is advisable to rough machine, then flame harden the surface and, finally, finish grind the part, thus eliminating the small amount of distortion that may occur in the hardening operation.

Equipment Used

Torches used in flame hardening are similar in their design and function to welding torches. However, they are usually of larger capacity, and for the majority of flame-hardening work, water-cooled torches are necessary. For small work, ordinary welding torches are employed.

Flame-hardening tips or burners are mainly of multiflame design. They usually require water cooling, since they must operate without backfiring for extended periods within the heat zone, and the *splash* of the flame is often directed back toward the tip or burner. Flame-hardening tips are generally designed for a specific application, although for certain types of work, tip and burner designs have

become fairly standardized. For example, a tip or burner for hardening shifter forks or locomotive valve links will require specially designed tips to conform to or reach the surface to be hardened, while in the case of a plane surface, a simple multiflame tip or burner will be satisfactory. The usual oxy-acetylene welding torches and tips are satisfactory for small work. Equipped with burners having two or more individual tips arranged in a common header, the use of oxy-acetylene welding equipment may be extended to handle a wide variety of small flame-hardening applications.

In flame-hardening operations, the quench may be provided by various means. For use in progressive flame hardening, tips or burners are usually designed with an integral water quench. In some cases, the heating burner or tip is followed by a separate quenching stream. Other applications are more conveniently handled by means of a water or oil immersion.

Oxygen and acetylene are most frequently used for flame hardening, although propane and butane are also employed. An adequate gas supply is important in flame-hardening work, since it is essential to complete the operation without interruption. Depending upon the size of the work and other factors, such as whether it is a single time or production operation, gas supplied from cylinders, manifolded cylinders or pipe lines may be used. Auxiliary equipment, such as pressure regulators, hose and control devices, must be of adequate capacity to supply the gases to the tips at the required rate.

Other auxiliary equipment includes carriage-type machines for mounting the torches and tips and propelling them over the surface to be hardened. These machines are identical in all respects with those used for cutting, and will not be described further. Cylindrical objects are usually handled by mounting the work between centers on a lathe and fixing the torch on the carriage in place of the usual tool post. Generally, auxiliary equipment for mounting the flame-hardening apparatus and for holding the work must be designed to meet the needs of a particular application.

Special flame-hardening machines to carry out the complete heating and quenching cycle are available for certain production operations. Gear-hardening machines are the most common examples of this type of equipment. However, in many cases, flame-hardening machines must be built especially for the specific application.

Common Applications

Flame hardening is particularly suited to the hardening of small contact areas on large sections which cannot be hardened by the furnace method because of the size of the object and the resulting distortion. The use of expensive liners, bushings or raceways can frequently be avoided by flame hardening the contact surfaces only, leaving the remainder of the object undistorted. The bearing surfaces of large gear teeth and roller or ball races are examples of such applications. Smaller objects can also be flame hardened economically when there is not a sufficient volume to warrant lighting a furnace for furnace treatment.

The flame-hardening process is extremely flexible as regards the size and shape of work that can be hardened with relatively simple portable equipment. The time required to flame harden is comparatively very short, and since the hardening is done on finished surfaces, considerable savings in machining and regrinding costs are possible.

Typical applications of flame hardening are shown in the accompanying figures. Figure 6 shows the hardening of the lower

Fig. 6.—Flame Hardening Lower Frame Casting for Power Shovel

frame casting used in a power shovel. The progressive method of hardening is being employed using tips having an integral water quench. Only one tip is in operation in this photograph. Figure 7 shows the hardening of sprocket teeth by the progressive method. The tips, which are designed to conform to the contour of the tooth face, are moved by mechanical means across the width of the tooth. The water quench is integral with the tips and can be seen behind the heating flames.

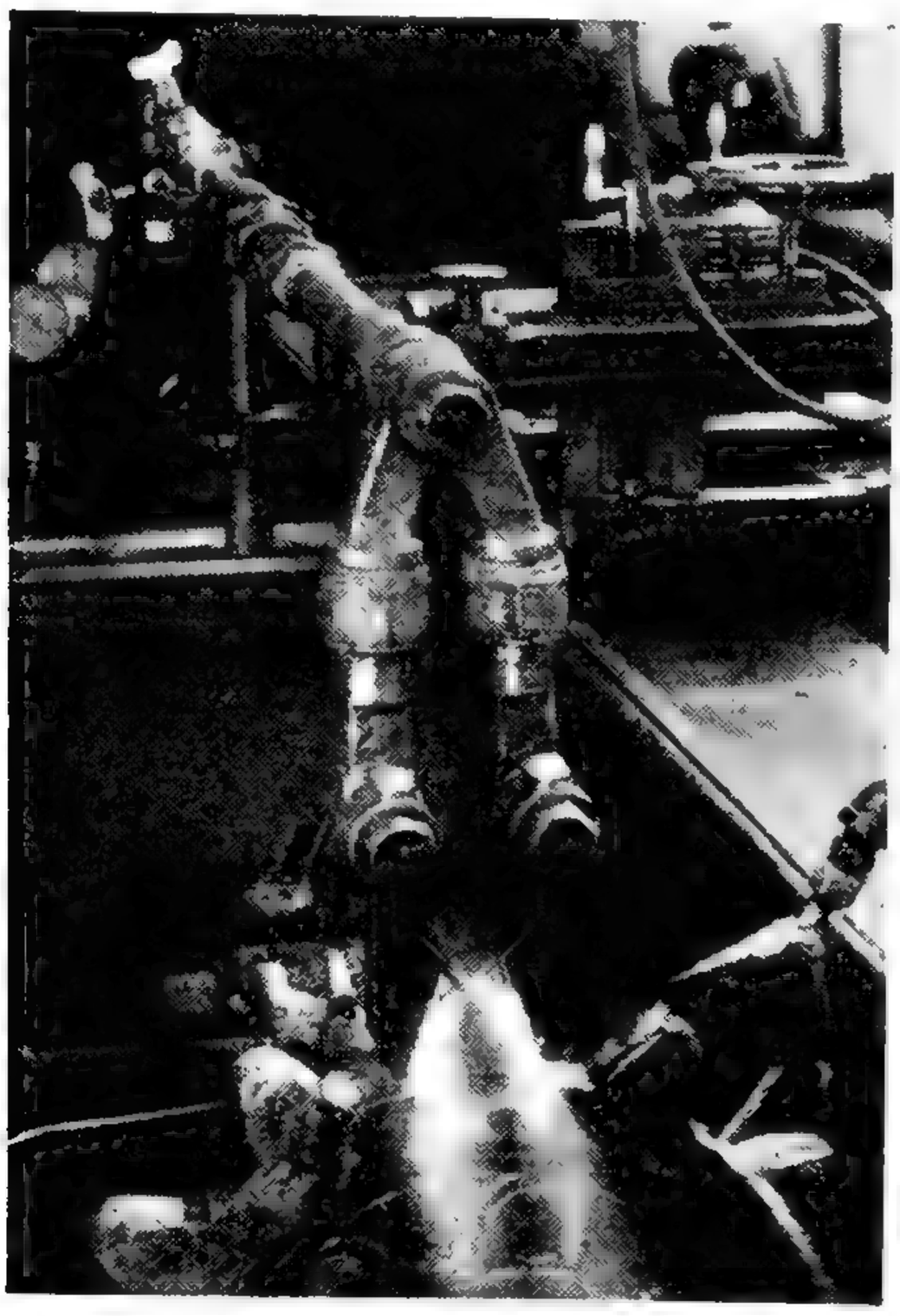

Fig. 7.—Flame Hardening of Sprocket Teeth by Progressive Method

In the right foreground can be seen an auxiliary cooling jet to prevent drawing the hardness of a previously hardened tooth.

Flame hardening by the progressive spinning method is illustrated in Fig. 8. Four tips are used for heating the shaft which is spun beneath them. The tips are followed by a separate water quench.

FLAME SOFTENING

Principles of Operation

When undesirable hardening occurs along a cut edge or from other working of steel, oxy-acetylene flames can be used either to prevent hardening or to temper an already hardened surface.

The point where oxygen cutting produces a hardened surface that may be detrimental subsequently has not been determined for all steels and for all applications. Furthermore, the hardness which may be objectionable varies from one application to another. For structural steel for example, oxygen-cut edges generally are adequate for the service properties specified for the base metal, such as tensile strength and ductility. In other applications, machinability may be the prime requisite.

Softening Techniques

The action of the oxy-acetylene flame in softening is identical to that in flame hardening and consists in rapidly heating the metal above the critical temperature. However, in the softening process, the quench is omitted and instead the part is allowed to cool slowly either in still air or packed in an insulating material, such as powdered asbestos, to retard the cooling rate. Because of the rapid heating effect of the flame, differential softening can be obtained as well as differential hardening.

When oxygen cutting high-carbon steels, it is possible to use flame softening in conjunction with the cutting operation to prevent undue hardness. In such applications flame softening may be used either as a preheat or a postheat treatment.

In the preheat method, a heating tip or head (without water quench), similar to that used for flame hardening, is mounted along the line of the proposed cut ahead of the cutting torch. The heat imparted by the heating tip reduces the quenching action of the cold base metal. Preheating with the oxy-acetylene flame is limited to thicknesses of $1^1/_2$ in., heating from one side only, and to 3 in., heating from both sides.

In the postheating method, the heating tips or heads are mounted immediately following the cutting tip. Sufficient heating tips or heads are used so that the speed of softening is equal to the cutting speed, and both operations proceed simultaneously. The flame-softening effect by postheating is more complex than by preheating, and combines a retarding action on the cooling rate with an actual softening effect on the already hardened surface. The temperature imparted to the plate in

postheating can be either above the A_1 point (supercritical anneal) or below this point (subcritical temper). The thickness of plate that can be softened by the postheating method is limited to approximately $1^1/_2$ in., heating from one side only, and to 3 in., heating from both sides of the plate.

At times it is not possible or convenient to flame treat and flame cut simultaneously. When simultaneous treatment cannot be applied, the cut edge can be tempered by heating. This tempering operation may be performed at any time after the cut has been made, provided the material does not crack during or after cutting. Cut surfaces 12 in. wide have been softened by this type of treatment, but even this thickness is not the limit, because heating heads can be made to cover even wider surfaces.

used for many years to restore ductility to auto body sheet which has been work hardened in deep drawing operations, heat from an oxy-acetylene hand torch being applied to deeply drawn areas. Some use of flame softening has been made in reducing hard spots on steel and cast-iron castings before machining as well as to produce softened areas that can be machined on objects which have been heat treated to high hardness. Spot softening can be done for machine work such as cutting keyways, drilling holes, altering hardened dies and cutting threads.

FLAME STRENGTHENING

In application, flame strengthening is practically identical with the flame-hardening treatment since hardness and tensile strength are parallel characteristics

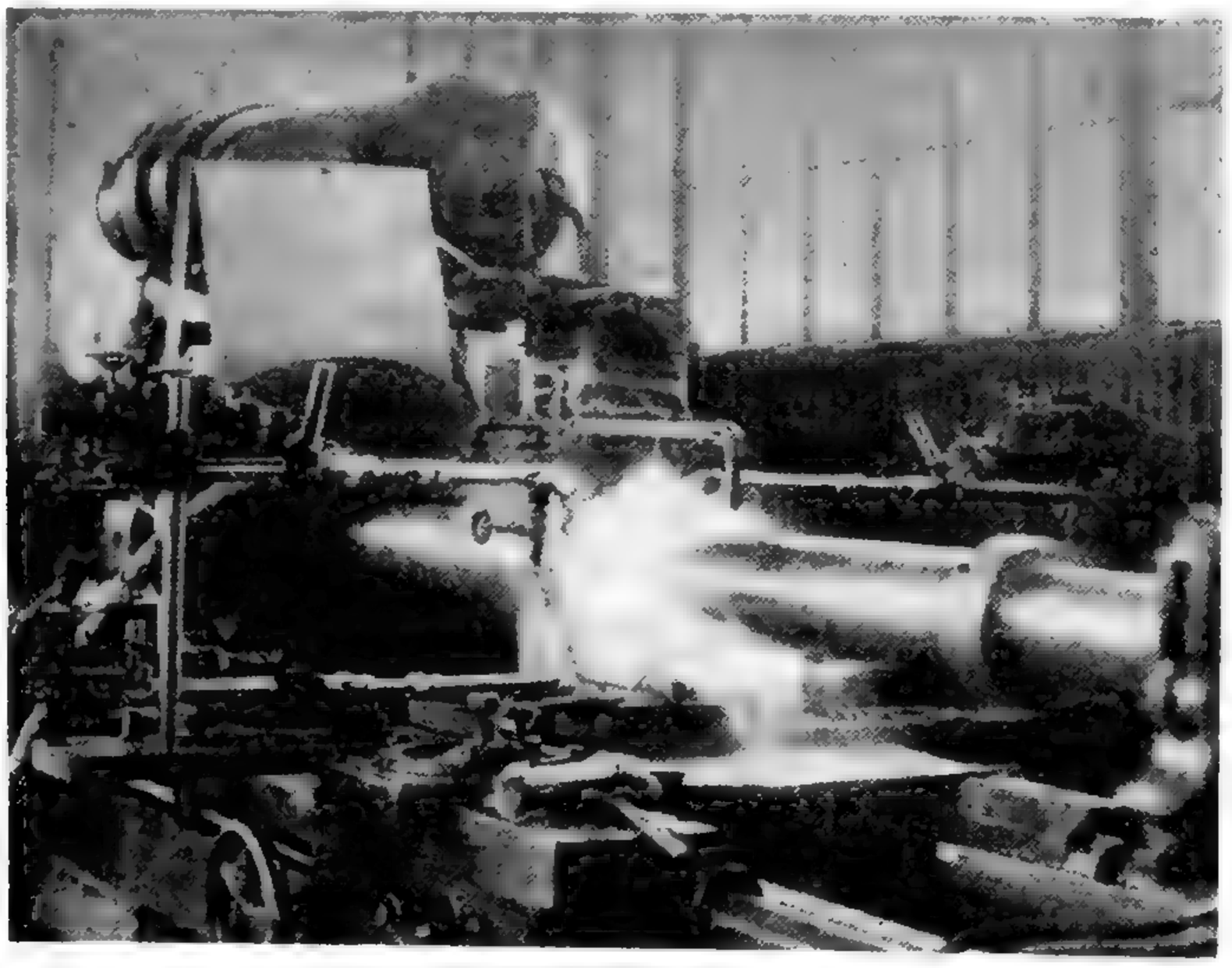

Fig. 8.—Progressive Flame Hardening 8-In. Diam. Shaft

Equipment Used

Standard torches, tips and heating heads, similar to those used for welding and flame hardening, are used for flame softening. Flame-hardening equipment with included quenching jets is, of course, not applicable. The same fuel gases are also used. Auxiliary equipment is usually provided as needed for each specific application.

Common Applications

The flame-softening process has been

in steel. The purpose of flame strengthening differs from flame hardening in that the intent is to strengthen parts locally in the regions which will have to withstand the most severe service conditions. The process is directed particularly at parts which are to be subjected to widely and frequently varying stresses conducive to failure by fatigue.

FLAME CLEANING

Flame cleaning has come into wide use in recent years for removing loosely ad-

hering mill scale and rust prior to giving steel its first shop coat of paint. It is also used to clean painted structures as a regular maintenance practice prior to repainting rusted surfaces.

The action of the flame-cleaning process is to remove by differential expansion the loosely adhering mill scale. This loose and semi-adherent mill scale by reason of its rapid expansion under the oxy-acetylene flame is caused to crack and scale off. The heat of the flame also turns any moisture present into steam, accelerating the process of scale removal and at the same time drying the surface ready for painting. In the case of a previously painted structure, the oxy-acetylene flame also aids in burning off the old paint.

Flame cleaning employs standard oxy-acetylene torches equipped with long extensions and special multiflame heating tips furnished with hard-faced skids which bear against the plate to be cleaned. The tips required for broad surfaces are wide flat-type tips capable of treating a wide area in a single pass. Circular multiflame tips are used for confined, hard-to reach areas and for working around rivet heads, gussets and splice plates.

Flame cleaning has found application for cleaning steel structures subject to various types of corrosive atmospheres. It has been used with excellent success to clean such diversified structures as water tanks and standpipes, railroad and highway bridges, structural steel being readied in the fabricating shop in advance of receiving its shop coat of paint before shipment to the erection site, and the hulls of ships.

FLAME STRAIGHTENING

In flame hardening mention was made of the fact that heating on one side of an object tended to have the effect of shortening the heated side. This fact is made use of in flame straightening. It is employed to straighten weldments which have been distorted due to a previous welding operation, and to remove buckling in plates resulting from a similar process. Flame straightening is also used to relieve rolling stresses in steel to restore its intended straightness.

FLAME SHRINKING

Flame shrinking has been placed in operation as a successful process for reducing the length of eye bars in railroad bridges where, because of long periods of service and consequent wear, the pins no longer fit snugly. Flame shrinking uses the oxy-acetylene flame as a means for heating the eye bar, the metal of which is then upset by mechanical clamps and jacks temporarily fitted.

BIBLIOGRAPHY

1. *Shortening, a New Old Method of Surface Hardening,* T. W. Lippert, Iron Age, August 8, 1935.
2. *Hardening Cast or Rolled Steel,* G. V. Slottman, Steel, November 9, 1936.
3. *Localized Surface Hardening,* R. L. Rolf, Steel, November 30, 1936.
4. *Hardening Iron and Steel with the Oxy-Acetylene Flame,* R. L. Rolf, ASM Metals Handbook, 1936 Edition.
5. *Surface Hardening with the Oxy-Acetylene Flame,* A. K. Seeman, Metal Progress, September 1937.
6. *Flame Hardening,* J. T. Howat, The Welding Journal, February 1938.
7. *Flame Hardening and Its Principles,* H. H. Langebeck, The Welding Journal, September 1938.
8. *Hardening Moly Steels; Abstract from Moly Matrix,* Steel, October 3, 1938.
9. *Report of Subcommittee on Flame Hardening,* Stephen Smith, American Society for Metals, January 16, 1939.
10. *Flame Hardening,* Stephen Smith, American Society for Metals, April 30, 1939.
11. *Surface Hardening and Hard Surfacing,* C. E. MacQuigg, The Welding Journal, June 1939.
12. *Surface Hardening and Hard Surfacing,* International Acetylene Association Report, Metal Progress, August 1939.
13. *Flame Hardening of Cast Iron,* F. G. Sefing, Iron Age, October 19, 1939.
14. *Flame-Hardening Methods,* Stephen Smith, Steel, November 13, 1939.
15. *Functions of the Alloying Elements in Steel,* E. C. Bain, U.S. Steel Corp., 1939.
16. *Flame Treating,* J. H. Zimmerman, The Welding Journal, February 1940.
17. *The Production Flame Hardening of Machine Parts,* J. Erler and P. H. Tomlinson, The Welding Journal, October 1940.
18. *Flame Hardening,* R. H. Zeilman, The Welding Journal, October 1940.
19. *Notes on Flame Hardening,* G. V. Slottman, July 1940.
20. *Cast Metals Handbook,* American Foundrymen's Association, 1940.
21. *Flame Machining, Control and Application,* G. L. Walker and W. G. Sylvester, The Welding Journal, February 1941.
22. *Uses of Flame Hardening in Machine Tool Production,* A. L. Hartley, The Welding Journal, October 1941.
23. *Flame-Hardening Malleable Iron,* Stephen Smith, American Foundrymen's Association, May 12, 1941.
24. *Flame Hardening of Round Surfaces,* Stephen Smith, The Welding Journal, July 1942.
25. *New Developments in Flame Hardening,* Stephen Smith, The Welding Journal, January 1943.
26. *Ordnance Flame Hardening,* Stephen Smith, The Welding Journal, November 1943.
27. *Flame Hardening in the Small Shop,* W. W. Sharar, The Welding Journal, January 1946.

28. *Flame Cutting, Flame Hardening and Welding on Railroads*, J. W. Kenefic, The Welding Journal, April 1946.

29. *The Metallographic Constituents of Steel and Cast Iron as Effecting Flame Hardening*, O. M. Harrellson, The Welding Journal, September 1947.

30. *Flame Hardening Locomotive Brake and Spring Rigging Pins and Bushings*, B. W. Covell, The Welding Journal, October 1947.

CHAPTER 27

IRON, WROUGHT IRON AND CARBON STEELS*

A. WROUGHT IRON

GENERAL PROPERTIES

WROUGHT IRON is a two-component metal consisting of high purity iron base metal and iron silicate. The iron silicate takes the form of a glass-like slag. These two materials are in physical association, as compared with the chemical or alloy relationship which generally exists between the constituents of other ferrous metals.

The iron silicate or slag content of wrought iron varies from about 1 to 3 or $3^1/_2\%$ depending upon the type or class of product. This constituent is distributed throughout the iron base metal in the form of threads or fibers which extend in the direction of rolling. The slag fibers are distributed so thoroughly throughout the iron component that there may be 250,000 or more to each cross-sectional square inch of finished material. This confers on the material a definitely fibrous structure which can be observed readily if a piece is nicked and fractured. A typical photomicrograph of wrought iron is shown in Fig. 1. Each of the two dissimilar materials that go to make up wrought iron has its own fusion temperature. The iron base metal, because of its low metalloid content, fuses at a temperature of about 2730°F., which is somewhat higher than the melting point of low- and medium-carbon steels. The slag component fuses at a temperature of about 2200°F., or several hundred degrees lower than the base metal.

The purity of the base metal gives wrought iron the ability to withstand higher temperature than other ferrous metals and, in general, it should be worked hotter for best results. Also, the protection afforded the metal during heating by the fluxing action of the slag has a beneficial effect in producing sound welds. A typical analysis of wrought iron follows:

Carbon, % max.	0.05 or under
Manganese, % max.	0.05 or under
Phosphorus, %	0.10 to 0.15
Sulfur, % max.	0.04 or under
Silicon, %	0.08 to 0.15
Slag, %	1 to 3.5

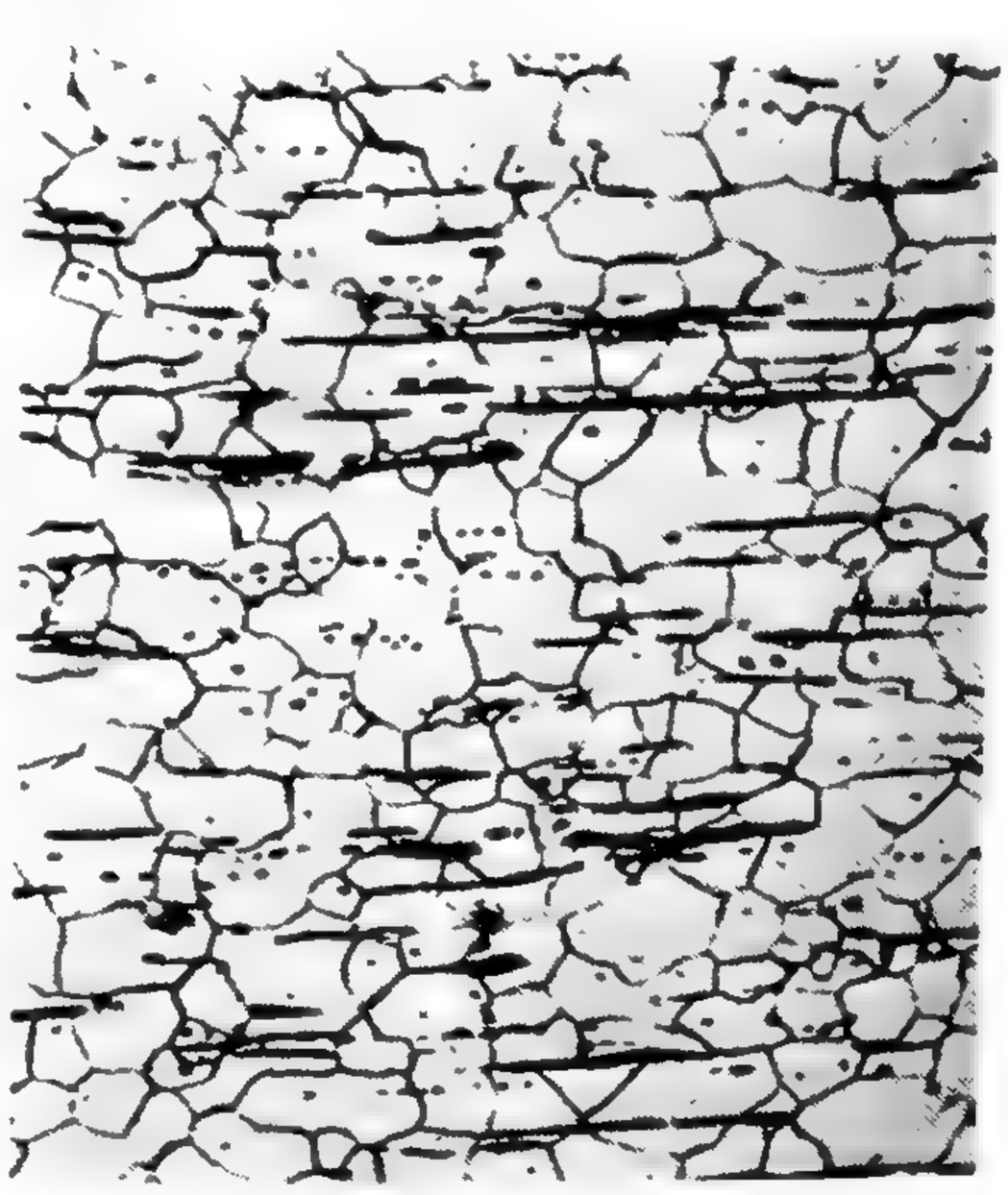

Fig. 1.—Typical Microstructure of Wrought Iron

Wrought iron can be welded easily by any of the commonly used processes, such as forge welding, resistance welding, metal arc welding, carbon arc welding and gas welding. The absence of the A_1 point in wrought iron is of importance in reducing strains due to welding and in

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eliminating air-hardening. However, internal strains cannot be eliminated as a factor, and stress relieving of welded structures, particularly where heavy sections are involved, is considered good engineering practice. Temperatures of 700 to 800°F. are usually sufficient to relieve stresses induced through expansion and contraction by the heat of welding. To avoid stress corrosion, stress relieving is particularly desirable for equipment that is to be used in certain types of service such as the handling of caustic solutions.

Table 1—Manual Oxy-Acetylene Welding of Wrought Iron

Thickness of plate, In.→ / Type of joint→	1/8 Single-Vee	1/4 Single-Vee	3/8 Single-Vee	1/2 Single-Vee	5/8 Single-Vee	3/4 Single-Vee	7/8 Single-Vee	1 Single-Vee
Angle (from perpendicular) deg.	30	40	40	40	40	40	40	40
Groove angle, deg.	60	80	80	80	80	80	80	80
Root opening starting end, in.	1/32	1/16	1/16	1/16	1/16	1/16	1/16	1/16
Root opening (18 in. from starting end), in.	1/8	3/16	1/4	1/4	1/4	1/4	1/4	1/4
Diameter of welding rod								
1st side, in.	1/8	3/16	1/4	1/4	1/4	1/4	1/4	1/4
Root side,[a] in.	1/8	3/16	3/16	3/16	3/16	1/4	1/4	1/4
Number of layers								
1st side	1	1	1	2	3	3	4	5
Root side[a]	1	1	1	1	1	1	1	1

[a] When a double weld is required, as for example under the ASME Boiler Code, Par. U-68 or U-69, a root bead is used.

NOTE: Use the tip size, oxygen and acetylene pressures recommended for mild steel of the same thickness.

ASTM *Specifications for Wrought Iron Plates* (Serial Designation A42) specifies the minimum requirements for the longitudinal mechanical properties of wrought iron plates produced by standard rolling operations as follows:

Tensile Strength, min., psi	48,000
Yield Point, min., psi	27,000
Elongation in 8 in. min., %	14

There is no difficulty in obtaining welds in wrought iron with properties equal to those of the base metal.

HOW TO WELD

Forge and Resistance Welding

When welding wrought iron by either forge or the resistance welding processes, the important point to keep in mind is that the metal must be worked at temperatures somewhat higher than steel. In forge welding, for example, wrought iron is worked at what is termed a *sweating heat*, which corresponds to a temperature of about 2500 to 2550°F. Wrought iron is a soft metal and is easily deformed at these temperatures.

When joining lengths of wrought iron pipe using upset welding, the best results are obtained by forcing the ends together with pressure that is just sufficient to produce a sound union. Excessive pressure usually results in pronounced upsetting action and localized thickening of the metal, which is frequently objectionable. A test or two are usually sufficient to enable the operator to determine the proper amount of pressure to use.

Gas Welding

The procedure for welding wrought iron by manual oxy-acetylene welding is practically the same as that used in welding mild steel of the same thickness. However, one important point to keep in mind is that the iron silicate or slag included in the metal melts at a temperature which is below the fusion point of the iron base metal. The melting of the slag gives the surface of the metal a greasy appearance. This should not be mistaken for actual fusion of the base metal and heating should be continued until the iron is fully melted.

The best oxy-acetylene welds are produced when complete fusion is obtained without excessive mixing of the base metal and weld metal. Too much agitation of the molten metal causes the formation of oxides which may become entrapped in

the weld. Ordinarily, just enough of the metal should be fused to provide a sound bond with the deposited metal.

The selection of the proper welding rod is important. Welding rods having a high carbon content or an alloy content intended solely to increase the strength of the deposited metal are not recommended. Filler metal conforming to Classifications GA60 and GB60 of the AWS-ASTM *Specifications for Iron and Steel Gas-Welding Rods* are suitable for welding wrought iron.

Table 2—Manual Shielded Metal-Arc Welding Procedures For Wrought Iron

Thickness of plate, in. → Type of joint →	1/4 Single-Vee	3/8 Single-Vee	1/2 Single-Vee	5/8 Single-U	3/4 Single-U	7/8 Double-U	1 Double-U
Angle from perpendicular, deg.	30	30	30	9	9	9	9
Groove angle, deg.	60	60	60	18	18	18	18
Radius, in.	None	None	None	1/4	1/4	1/4	1/4
Root face, in.	0 to 1/16	0 to 1/16	0 to 1/16	3/32	3/32	3/32	3/32
Root opening, in.	5/32	5/32	5/32	None	None	None	None
Number of passes	3	4	5	6	8	9	10
Diameter of electrodes, in.	3/16	3/16	3/16	3/16	3/16	3/16	3/16
Current, amp.	170	170	180	180	180	180	180
Rate of travel of electrode, in. per min.							
1st bead—1st side	8	8	7	7	7	6	6
Intermediate beads—1st side	5	5	5	5	5	5	5
Last bead—1st side	5	5	4	4	4	4	4
1st bead—2nd side[a]	5	5	4	4	4	6	6
Intermediate beads—2nd side-	...	...	...	...	..	5	5
Last bead—2nd side[a]	...	...	...	...	...	4	4

[a] Not used unless a double weld is specified.

When oxy-acetylene welding wrought iron, best results are usually obtained by using a neutral flame. A straight sequence, wherein subsequent layers about 3/16 to 1/4 in. high are deposited for the full length of the joint, or a cascade sequence may be used. In using the cascade sequence for a plate 5/8-in. thick, for example, the weld is started by depositing a root bead about 1 1/2-in. long. A second bead is deposited over the root bead and extended about 1 1/2 in. beyond it, forming a new root bead. The third bead completes the weld for the first 1 1/2 in., forms a second bead for the next 1 1/2 in. segment and a root bead for another 1 1/2 inches. The weld is completed by a continuation of this sequence.

Satisfactory oxy-acetylene welding procedures for wrought iron are shown in Table 1.

Shielded Metal-Arc Welding

In shielded metal-arc welding wrought iron, the best welds are produced when the welding speed and current are decreased slightly below those used for the same thickness of mild steel. A reduced speed is desirable because the pool of molten metal immediately following the arc is thereby kept molten for a longer period of time, making for greater elimination of the gases and affording the entrapped slag an opportunity to float out of the weld metal. The slightly lower current, particularly in welding thin sections, prevents burning through the material.

Excessive penetration into the base metal should be avoided. The penetration should be no greater than that required to obtain a sound bond between the deposited metal and the base metal, because excessive fusion tends to carry slag into the weld metal. Thorough cleaning of each bead of oxide or other accumulated surface coating prior to depositing subsequent beads is recommended to insure soundness of the deposited metal.

Filler Metal.—In general, it is desirable to have the deposited weld metal as close in composition as possible to the wrought iron base metal. It should be recognized, however, that during the welding operation, the metal deposited undergoes a change in composition and some of the elements such as carbon, manganese and silicon are lost through oxidation. Thus, the electrode should contain sufficient quantities of these elements to compensate for the loss during welding so that the resultant weld metal will closely approach the chemical composition of the base metal. It is suggested that electrodes

selected for welding wrought iron be in accordance with the requirements of the E60 Series of classifications of the AWS-ASTM *Specifications for Mild Steel Arc-Welding Electrodes.*

Specifications for manual shielded metal-arc welding procedures for wrought iron are shown in Table 2.

Carbon-Arc Welding

Carbon-arc welding has been used with very satisfactory results in welding wrought iron sections. The procedure is the same as that used for mild steel except that the arc voltages and currents should be slightly lower than those recommended for mild steel.

COMMON APPLICATIONS

Fabrication of wrought iron piping by welding has increased in popularity each year, and welded coils are almost exclusively used in radiant heating systems, snow melting installations, skating rinks and in many industrial processes where heating or cooling coils are required. Large diameter wrought iron pipe, fabricated from plate for sewer outfalls, penstocks, etc., is usually welded. Beveled-end pipe is usually purchased, but no difficulty has been experienced in welding pipe cut in the field with a rotary cutter and reamed, as the cutter wheel imparts a slight bevel to the ends. Industrial applications include tanks, smokestacks, ballast deck plates for railway bridges, pier protection plates, trash racks and many other applications where welded wrought iron equipment is commonly used. Old wrought iron structures, such as bridges, may frequently be strengthened by welding, thus enabling them to carry present-day loads with safety. Ornamental wrought iron and wrought iron furniture are commonly welded.

B. INGOT IRON

GENERAL PROPERTIES

Ingot iron is an open-hearth iron very low in carbon, manganese and other elements. Like most pure metals, ingot iron is soft and malleable. In general, ingot iron has a total metalloid content of less than 0.10%, exclusive of copper, which is considered beneficial wherever the ingot iron is to be used as a corrosion-resisting material. Selected ingot iron with specified copper contents is available. A typical analysis of ingot iron follows:

Carbon, %	0.015
Manganese, %	0.035
Phosphorus, %	0.005
Sulfur, %	0.025
Silicon, %	0.003

As would be expected, the photomicrograph of ingot iron shows it to be pure ferrite as shown in Fig. 2. The basic composition is quite similar to wrought iron which has, in addition, the slag stringers shown in Fig. 1 which develop the well-known fibrous structure of wrought iron.

Fig. 2.—Typical Microstructure of Ingot Iron

Ordinary steel has dark pearlitic areas besides the white ferritic grains. Of course these darker regions occur as a result of the presence of an appreciable amount of carbon; some five to ten times that found in ingot iron.

HOW TO WELD

In considering the welding of ingot iron, attention must be given to the mechanical properties of the material as outlined in Table 3.

Table 3—Average Mechanical Properties of Ingot Iron

Ultimate tensile strength, psi.	45,000
Yield strength, psi.	30,000
Endurance limit (reverse bending), psi.	26,000
Elongation in 2 in., %	35
Reduction in area, %	73
Modulus of elasticity, psi.	30,000,000

As it contains practically no carbon, ingot iron will not harden as a result of

welding. No hardened heat-affected zone can exist. However, the critical working range that appears between 1580 and 1920°F. must be considered. Any hot fabrication should be done outside this range if checking or cracking is to be avoided. Because of its composition and very good ductility, ingot iron may be worked both at a white heat and at a dull red heat (below 1500°F.) without any trouble.

Because of purity, uniformity of grain structure and freedom from gas-forming metalloids, ingot iron possesses excellent welding characteristics. It may be joined by any of the common welding processes including the metal-arc, gas and resistance welding processes.

Metal-Arc Welding

When metal-arc welding is employed, it is desirable to use covered electrodes. As ingot iron is an extremely pure iron, its melting temperature is somewhat higher than the commonly used impure irons, or steels. Consequently, ingot iron must be worked hotter for the best results. To gain the increased heat, welding speeds are reduced slightly below those used for the same thickness of mild steel.

Electrode choice may be made on the same basis as for mild steel. Where sheet less than $^1/_8$-in. thick is to be welded, all-position electrodes may be specified. For welding plates in the flat position, downhand electrodes may be used.

Table 4 shows the welding rod and electrode diameters for welding various thicknesses of ingot iron. Deviation from these sizes may be found advisable under some conditions of welding.

Table 4—Recommended Filler Metal Sizes for Various Thicknesses of Ingot Iron

Thickness of plate	Electrode Diam. (Metal-Arc Welding), In.	Welding Rod Diam (Oxy-Acetylene Welding), In.
16 ga. and lighter	$^1/_{16}$	$^1/_{16}$
16 ga. to $^1/_8$ in.	$^3/_{32}$ or $^1/_8$	$^1/_8$
$^1/_8$ to $^3/_{16}$ in.	$^5/_{32}$	$^5/_{32}$
$^3/_{16}$ to $^1/_4$ in.	$^3/_{16}$	$^3/_{16}$
$^1/_4$ to $^3/_8$ in.	$^1/_4$	$^1/_4$

Oxy-Acetylene Welding

Oxy-acetylene welding ingot iron is quite similar to oxy-acetylene welding of low-carbon steel. Welding rods of the same analysis as the base metal will prove to be the most satisfactory. For an occasional welding job, shearings of the base metal may be used as filler metal although prepared rods are to be preferred.

Resistance Welding

Resistance welding includes all of the many processes such as spot welding, flash welding, upset welding, seam welding, etc. The higher melting point of ingot iron compared with mild steel, and the decidedly greater heat conductivity, indicate the need for greater welding heat.

C. CARBON STEELS

GENERAL PROPERTIES

Carbon steels are the steels which owe their properties chiefly to the presence of varying percentages of carbon without substantial additions of other alloying elements. They are so designated when no minimum content is specified or guaranteed for such alloying elements as aluminum, chromium, columbium, molybdenum, nickel, titanium, tungsten, vanadium or zirconium; when specified copper contents are below the specification minimum of 0.20%; and when specified or guaranteed manganese and silicon contents do not exceed 1.65% and 0.60% respectively.

As a matter of convenience carbon steels are commonly designated as *low-carbon* steel, *medium-carbon* steel and *high-carbon* steel.

In general, low-carbon (or mild) steel is carbon steel containing 0.30% C or less by ladle analysis, medium-carbon steel is carbon steel containing more than 0.30% but not more than 0.45% C by ladle analysis, and high-carbon steel is carbon steel containing more than 0.45% C by ladle analysis. Some of the low-carbon steels contain a minimum of 0.20% copper, and are known as *copper-bearing* steels. From the standpoint of welding, these steels require no special considerations not otherwise required for low-carbon steels.

With the increased use of welding in different industries, material specifications have been developed to cover carbon steels suitable for welding. Such specifications have generally been developed to meet the needs of a particular industry and they are therefore covered separately in the chapters of this HANDBOOK dealing with specific industrial applications.

HOW TO WELD

General

The ability of carbon steel to be welded, other factors such as thickness, geometry of joint, etc., not considered, is a function of its carbon content. While all carbon steels can be welded by at least one process, in general, the higher the carbon content the more difficult it is to weld them and the more special the precautions required.

Arc Welding

All carbon steels can be welded by bare or shielded metal-arc welding. Where the carbon content does not exceed 0.30 to 0.35%, depending on the thickness of the material, this material can be welded by any proper procedure which will assure proper penetration and fusion. As the carbon content increases it becomes necessary to apply preheat and postheat treatments and to maintain proper interpass temperature control. The high-carbon steels are only welded for very few applications, such as the repair of cracked or worn parts of high-carbon steel, or the joining of rail ends.

Filler Metal.—For the low-carbon steels, mild steel electrodes of the E60 series of classifications may be used. These same electrodes may be used for medium- and high-carbon steels where the strength or other requirements permit their use. More recently so-called *low-hydrogen electrodes* have been developed (E6015 and E6016) and these have been helpful to some extent in reducing the amount of special precautions such as preheating and postheating required when welding the medium- and high-carbon steels.

Gas Welding

Gas welding carbon steels is very largely confined to the oxy-acetylene process, other fuel gases usually not providing a sufficient amount of heat. In addition to welding these steels with welding rods of similar composition, the method of welding known as braze welding, using nonferrous welding rods, is used. Braze welding is commonly used to repair broken or worn parts or to apply a surface layer of a metal having special properties for specific service requirements. Where preheating is necessary, this can frequently be accomplished with the welding torch so that the temperature gradient can be made less sharp.

Resistance Welding

All of the resistance welding processes may be used for welding carbon steels.

Carbon steel having a carbon content of 0.15% or less can be very readily spot and seam welded. Where the carbon content is higher, special techniques, for which provision is sometimes made in the welding cycle, are required. It is also possible to projection weld steels with higher carbon contents, which might otherwise be difficult to spot weld, because of the greater concentration of heat and pressure afforded by the projections.

Flash and upset welding may be used to weld the carbon steels over a very wide range of carbon content.

Other Processes

Brazing, forge welding, thermit welding and all of the other welding processes can be used to weld the low-carbon steels and the medium-carbon steels, with some precautions. Thermit welding is commonly used to weld the high-carbon steels, as in rail welding, and forge welding is used to a lesser extent.

Because the specific welding requirements for a given application govern the welding procedure to be used and the limitations which may exist, more specific information on the welding of carbon steels has been included in the appropriate chapters covering industrial applications. More basic information on such aspects as metallurgy, design of joints, properties of joints, etc., and on the use of specific welding procedures will be found in chapters of this HANDBOOK dealing with these subjects.

BIBLIOGRAPHY

1. *Useful Information on Armco Ingot Iron*, Armco Steel Corp.

2. *Welding and Flame Cutting Wrought Iron*, A. M. Byers Co.

3. *The Effects of Carbon on Welding of Plain Carbon Steels*, a review of the literature, W. Spraragen and G. E. Claussen, The Welding Journal Res. Suppl., August 1939.

4. *Welding Copper Steels—A Review of the Literature*, W. Spraragen and G. E. Claussen, The Welding Journal Res. Suppl., September 1939.

5. *Mechanical Characteristics of Resistance Welds in Plain Carbon Steels, A Review of the Literature*, W. Spraragen and G. E. Claussen, The Welding Journal Res. Suppl., July 1944.

NOTE: See bibliographies in chapters on processes and applications for other references.

CHAPTER 28

CAST IRONS AND CAST STEELS*

A. CAST IRONS

GENERAL PROPERTIES

THE TERM CAST IRON is applied to a wide variety of gray iron compositions which are defined in specifications as regards chemical composition and mechanical properties. ASTM *Standard Specifications for Gray Iron Castings* classifies gray irons on the basis of tensile strength, in seven classes:

Class No.	Minimum Tensile Strength, Psi.
20	20,000
25	25,000
30	30,000
35	35,000
40	40,000
50	50,000
60	60,000

Typical compositions of high strength cast irons as given in the 1948 edition of the *Metals Handbook* are shown in the following table:

Approx. Strength, Psi.	Chemical Composition, %							
	Total C	Si	Mn	S	P	Ni	Cr	Mo
50,000	3.15	2.25	0.70	0.10	0.15	1.00	0.50	0.80
50,000	3.05	1.70	0.75	0.10	0.20	..	0.50	0.50
55,000	3.05	2.10	0.80	0.10	0.10	0.50	0.90	0.50
60,000	3.00	2.15	0.80	0.10	0.14	1.60	..	0.80
70,000	2.70	2.30	0.85	0.08	0.10	0.80	0.20	1.00

Navy Department Specification 46-I-9 for *Gray Iron Alloy Castings* (*Scale Resisting*) defines chemical composition and the mechanical properties desired as follows:

Chemical Composition, %								Tensile Strength, psi.	Brinell Hardness
Total C	Si, Max.	P, Max.	S, Max.	Mn	Ni	Cr	Cu		
2.00	1.25	0.2	0.10	0.8	1.2	2.0	5.0	25,000	120
3.00	2.20	...	....	1.3	15.0	3.5	7.0	25,000	180

Navy Department Specification 46-I-6c for *Gray Iron Castings* lists three classes:

(*A*) Light castings—Minimum tensile strength 18,000 psi.

(*B*) Medium weight castings—Minimum tensile strength 21,000 psi.

(*C*) Heavy castings—Minimum tensile strength 24,000 psi.

Cast irons for various uses are defined in the following ASTM Specifications:

Designation	Title of Specification
A44	Pit-Cast Iron Pipe for Water and other Liquids
A74	Cast Iron Soil Pipe and Fittings
A126	Gray Iron Castings for Valves, Flanges and Pipe Fittings
A142	Cast Iron Culvert Pipe
A159	Automotive Gray Iron Castings
A190	Gray Iron Castings, Light Weight and Thin Sectioned
A278	Gray Iron Castings for Pressure-Containing Parts for Temperatures Up to 650°F.

From the above, with particular reference to the compositions of the high-strength cast irons shown, it is apparent that the wide variations as regards total carbon and percentage of the alloying elements, nickel, chromium, copper and molybdenum control the tensile properties of these alloys. General wear resistance of gray cast iron is a function of its hardness. Increased hardness is usually a function of the combined carbon content. Increased silicon content decreases resist-

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ance to wear but increases resistance to acids; increased nickel content is associated with increased tensile strength and resistance to corrosion. In general, cast irons, except those with high silicon content, are not suitable for use with either concentrated or diluted acids but they are resistant to many alkaline and caustic solutions. The tensile strength of the common grades of cast iron is within the range of 30,000 to 40,000 psi. Cast irons intended for use with the more severe corrosive solutions are alloyed with high percentages of nickel (13 to 14%), copper (4 to 7%) and chromium ($3^1/_2$ to 5%). The yield point of all cast irons is not definite as in other ferrous alloys and, for practical purposes, it may be said that for gray cast irons the yield point and ultimate strength are coincident. The compressive strength of cast iron is from $2^1/_2$ to $4^1/_2$ times greater than its tensile strength. The impact resistance of cast iron is generally low, particularly when the phosphorus content is at the maximum given in the applicable specifications. Regardless of the relatively low tensile properties of unalloyed cast irons and those wherein the alloying elements are present only in very small percentages, they still are important engineering materials and find many applications, particularly under conditions of static loading and in the fabrication of lightly stressed process equipment, domestic machinery, gasoline engine blocks and in other applications where long life is expected without severe thermal and mechanical shocks.

HOW TO WELD

Preparation for Welding

Because of the special characteristics of cast iron, the arc- and gas-welding processes probably cover most of the miscellaneous welding applications. Thermit welding is used for repair of larger structures. Preparing cast iron for arc or gas welding or torch brazing requires joint preparation by chipping, machining or sawing. The increased amount of free carbon at the weld zones is particularly objectionable when it is intended to arc weld the joint, and may be objectionable even for gas welding. A 90-deg. groove angle is applicable for either gas welding or torch brazing for thin-walled assemblies. For heavier assemblies, the 90-deg. groove angle is satisfactory if a double-vee groove is used. Where the weld must be made from one side only, it is often advantageous to increase the groove angle to 120 degrees. For arc welding the groove angle is usually not more than 60 degrees. The root opening must be sufficient to permit fusion with the root faces and the backing plate, and in thick-walled assemblies particularly, must be sufficiently wide to permit uninterrupted manipulation of the torch or electrode.

Preheating.—The preheat temperature is greatly influenced by the chemical composition of the casting. When the volume of the free carbon in the base metal is excessively high the amount of carbon which migrates into the weld metal may exceed that which it may hold in solution. In such cases the excess carbon is precipitated at the grain boundaries thus weakening the weld metal, and causing shrinkage stresses which promote the development of cracks or fissures. Further complications as regard weldability occur when the sulfur content of the base metal approaches the upper limits allowed in the specifications, particularly when the phosphorus content also is near the upper limit. A preheat temperature of 200 to 400°F. is usually sufficient to improve the performance of nickel core electrodes when the restraint is not too severe or when the weld can be completed in a few passes.

Processes Used

Arc Welding.—Carbon is present in cast iron in two forms, namely, as combined carbon, that is, carbon in solution as in steels, and as free carbon in the form of minute graphite flakes. The presence of the graphite flakes renders cast iron non-homogeneous and therefore a brittle material with low ductility. As previously shown the ultimate strength of commercial grades of cast iron varies within the range of 20,000 to 60,000 psi. These factors require careful consideration when arc welding cast iron.

As noted in Chapter 43 and elsewhere in this Handbook, arc welding produces longitudinal residual stresses in a weld approaching the yield point of the weld metal. For mild steel these stresses average 45,000 psi. and in a transverse direction the stresses average 15,000 psi. It must be borne in mind that mild steel is ductile and therefore it deforms in the course of welding, thus participating in the

absorption of the weld stresses by plastic deformation along and perpendicular to the weld zone.

Since cast iron is not ductile and therefore is not capable of plastic deformation, the base metal does not participate in the absorption of the weld stresses. Correspondingly, the requirement for the weld metal to absorb the shrinkage stresses is exaggerated in arc welding. For this reason, it is evident that welding of cast iron with mild steel electrodes is usually not practical.

Cracks in castings are frequently repaired by a method known as *studding* in which holes are tapped and drilled into the casting on each side of the fracture and studs screwed into these holes. A mild steel weld deposit is then made corresponding to a butt strap in a riveted splice. The basis of design for such a repair is similar to the basis of design for a riveted splice. The studs are spaced at approximately the same pitch as rivets and the shear strength of the joint is computed on the basis of the projected area between the studs and the fracture. The depth of tap is made to suit the stud used. Since the weld is stronger in tension than the cast-iron base metal, the thickness of the weld and the height of stud are appreciably less than the cast iron at the point of fracture. A typical repair by studding is shown in Fig. 1. The transverse strength of such joints when properly executed equals the shear value of the studs. Inasmuch as the weld metal often breaks away from the casting in course of cooling, these joints are seldom reliable for tightness against fluids or gases.

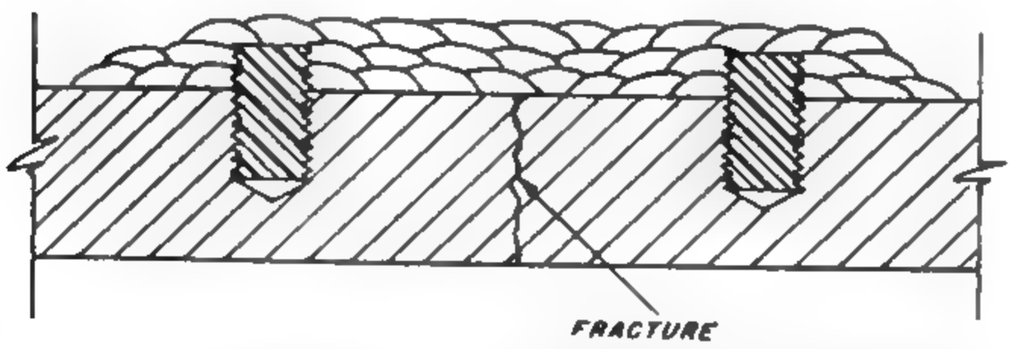

Fig. 1.—Repair of Casting by Studding

At present nickel core electrodes are often used, particularly for maintenance work. Their prime virtue is the relatively low yield point of cast nickel, which is the weld metal deposited by them. While these electrodes are satisfactory for many applications, the metal deposited by them is susceptible to cracking in thick sections, particularly when the weld is restricted considerably.

When welding with nickel core electrodes, d.c., reverse polarity is used at the lowest practical current values. The weld increments should be not more than 3 inches. When no preheating has been applied, the interincrement temperature must be kept below 200°F. When preheating is applied, the interpass temperature must be strictly observed. The weld metal deposited from nickel core electrodes does not give full color match. The weld metal is readily machinable and particularly in thin sections it does not render the weld zone of the base metal unmachinable.

Gas Welding.—By the use of gas welding, both of the shortcomings of cast iron as regards lack of ductility and its consequent inability to resist thermal stresses can be successfully overcome. To gas weld successfully, it is necessary to reduce the existence of sharp thermal gradients between the weld zone and the mass of the weldment. This requirement often limits the application of gas welding and it is preferable to preheat the entire casting to be welded even at times when this requires the construction of a special furnace. Exceptions to the requirement of total preheating are thin sections which are wholly unrestricted.

The normal welding procedure for gas welding is to preheat the weldment to a temperature within the range of 750 and 900°F.

Preheating is performed in various ways, depending upon whether a single weldment, as in maintenance, or systematic production, as in salvage plants, is involved. For small objects weighing less than 25 lb., preheating by the use of welding torches is satisfactory. Larger objects may be preheated by the use of fuel oil or aspirator-type gas burners or charcoal furnaces or by induction heating. Figure 2 shows a portable induction furnace for preheating and stress relieving cast-iron engine blocks which are repaired by gas welding. This design was employed for the preheat and postheat treatment of Diesel engine exhaust headers in a large salvage plant operated during the war by a Naval activity.

Welding is performed using a neutral flame and applying a cast-iron welding rod with the backhand technique. Fluxing is employed sparingly as warranted by the presence of impurities, or to increase wetting of the deposit. While there are prefluxed welding rods available, most welders prefer to apply flux by dipping the hot welding rod into the flux and transferring the flux into the weld as required to overcome momentary difficulties. Medium or high velocity torch tips of the same kind used in welding wrought steel are preferred to the low-velocity, bulbous-flame type which is used in welding nonferrous metals. In actual deposition of the welding rod, the inner cone of the flame is directed against the tip of the welding rod melting it off at the rate indicated by the wetting of the deposited metal. The preferred technique is to deposit the weld in layers not exceeding $^1/_8$-in. thick. The filler metal used is cast iron in the shape of square or round cast bars. The composition of these welding rods is usually controlled so that their melting point is at the lowest level practicable and so that they are free of nonmetallic inclusions, and low in both phosphorus and sulfur.

On completion of the weld, the entire casting, or as much of it as practicable, must be covered with suitable high temperature insulating material, such as asbestos cloth or paper, to prevent sudden chilling of the weld zone or in the case of weldments of considerable mass the development of severe thermal gradients.

For fully restrained welds, for welds intended for severe service and when the weldment is to be subject to machining to close tolerances, it is necessary that the welds be thermally stress relieved. The general practice in stress relieving

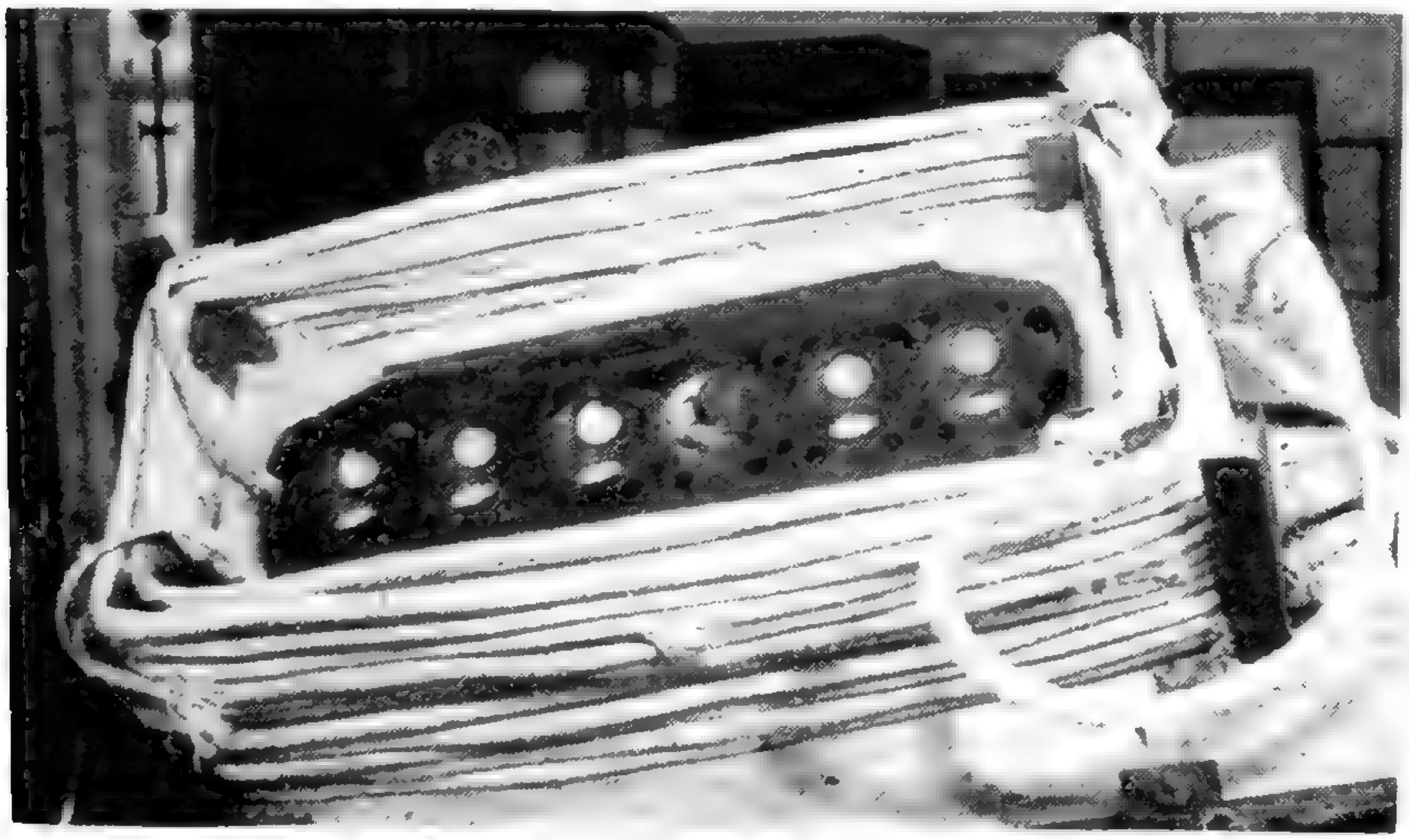

Fig. 2.—Induction Furnace for Preheating and Postheating Engine Blocks

welded cast-iron structures is to apply the postheat immediately upon completion of the weld, raising the temperature at a rate which permits uniform heat absorption over the entire mass of the structure to 1100–1150°F., and holding the weldment at that temperature for not less than 1 hr. per in. of thickness. Even greater care must be exercised in cooling the weldment and the cooling rate should not exceed 50°F. per hr. until the weldment has cooled at least to 700°F. Proper cooling may usually be accomplished by leaving the weldment to cool in the stress-relief furnace. (For further information on stress-relief heat treatment see Chapter 43.)

Color matching in gas welding is very good, machinability is good and when

stress relieved the casting may be even more serviceable than it was prior to the heat treatment.

Braze Welding.—For certain applications where the weldment is not subject either to atmospheric or electrolytic corrosion or to thermal stresses, such as gears and certain engine or machine frames, cast iron may be repaired by braze welding using a nonferrous filler metal, such as Naval brass (usually 60% Cu, 39.25 Zn, 0.75 Sn). The advantage of using nonferrous filler metals is that the melting point of these nonferrous materials is several hundred degrees lower than that of cast iron. Therefore, the work can be accomplished using lower heat input. Also the rate of deposition is greater permitting speedier completion of the work. In addition, by virtue of the low yield point of the nonferrous filler metal, the development of thermal stress on completion of the weld is less severe; therefore, control of the cooling rate is less critical and stress-relief heat treatment is not required in most cases. Obviously, there is no color match; however, machinability of the weld zone is not affected and may be even improved. The strength of the joint is fully comparable to that obtained with cast-iron filler metal.

Brazing

Ordinarily it is not possible to secure a satisfactory high-strength bond by brazing cast iron to cast iron or to other metals using silver brazing alloys. The primary difficulty is the presence of constituents in the cast iron which will prevent bonding or, in some cases, even wetting of the surface. Principally, graphitic carbon, but also the high silicon content and included sand particles, will do just that. Considerable success is being obtained with a proprietary electrochemical method of surface cleaning. In this process the objects are immersed in a catalytic salt bath and by alternately reversing the polarity, oxidation and reduction occur in successive cycles. The treated surfaces are free of dirt, oxides, graphite or silicates, hence fully suitable for brazing.

Thermit Welding

Thermit welding of cast iron is applied to heavy structures such as machinery bases or frames. Thermit welding is described in detail in Chapter 19.

Although the weld metal is steel, both it and the weld zone of the base metal are usually machinable by reason of the slow cooling obtained with this process. There is good color matching and if preheating is properly controlled the warpage is not substantial. The success of the operation depends on the judicious preparation of the fracture as regards the volume of metal removed and the application of preheating to those members of the structure which may otherwise produce restraint on the weld. The success of the operation is not always predictable even though the above precautions are taken.

Other Processes

Several non-welding methods using both metallic and nonmetallic fillers are in use for minor cast-iron repairs. These are described in the AWS *Recommended Practices for Salvaging Automotive Gray Iron Castings.*

COMMON APPLICATIONS

The earliest application of cast iron as an engineering material was for low-pressure steam engines. At present the foremost application of cast iron as an engineering material is in the form of gasoline engines. The greatest tonnage of cast-iron products is represented by soil pipes and other cast-iron pipe products used by the processing industries. Cast iron is an important material in the fabrication of chemical equipment, in the form of leaching kettles and shells of heat exchangers. Cast-iron machine parts form the greater portion of various types of industrial machinery used in weighing, packaging, conveying, printing machines and many other applications where the prime requirement is resistance to atmospheric corrosion and wear, rather than high fatigue value. Another important application of gray cast iron is for frames of large machines functioning at slow production rates. By reason of the appropriate damping characteristics of cast iron, it is a preferred material for machine bases and machine tools. This property is being exploited by the use of low-alloy, cast-iron crankshafts and camshafts in automotive and Diesel engines. Figure

3 shows a cast-iron Diesel engine exhaust head which has been repaired by arc welding. Figure 4 shows a cast-iron compressor head repaired by gas welding.

Cast iron is the most commonly used material in the fabrication of domestic heating plants, heat exchangers and radiators. Cast-iron valves in all sizes are used in cast-iron pipe lines. Cast iron is still employed, though not as frequently as in the past, for ornamental purposes in building contruction in the form of sculptural plaques, grills, marquees, fences and gates. Owing to its long life cast iron is regarded as a good building material, although its use is limited to ornamental purposes, and for lighter columns such as Lally columns.

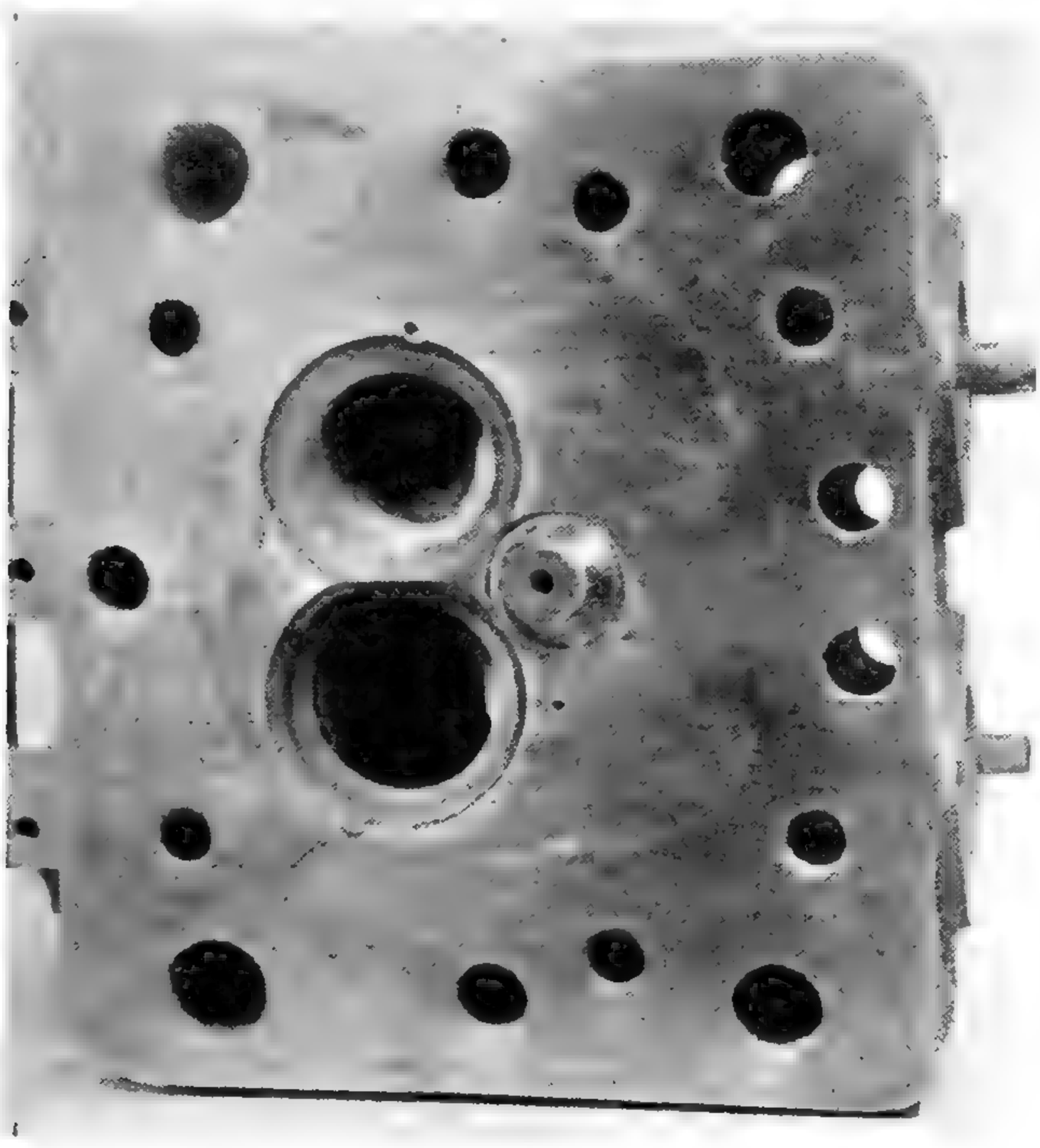

Fig. 3.—Cast Iron Diesel Engine Exhaust Head Repaired by Arc Welding

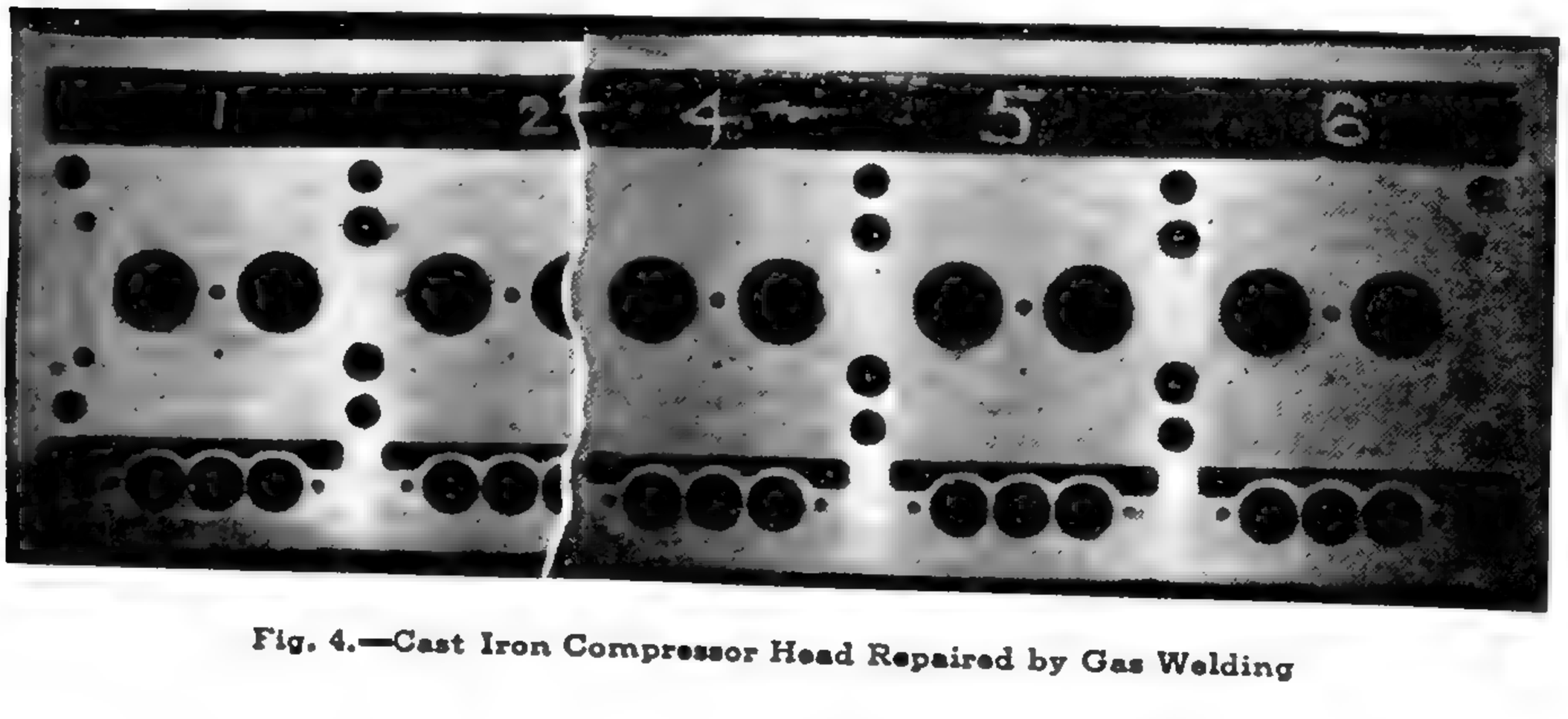

Fig. 4.—Cast Iron Compressor Head Repaired by Gas Welding

B. CAST STEELS

GENERAL PROPERTIES

The wide variation of the chemical compositions of cast steels renders it practicable to produce steels having mechanical properties of correspondingly wide range. The ASTM requirements for steel castings are expressed in grades denoting mechanical properties without reference to chemical composition. These requirements are as follows:

Grade	Tensile Strength, Psi. Min.	Yield Point, Psi. Min.	Elongation in 2 In., %
	ASTM A27 – 46T		
60-30	60,000	30,000	24
65-35	65,000	35,000	24
70-36	70,000	36,000	22
	ASTM A148 – 46T		
80-40	80,000	40,000	18
80-50	80,000	50,000	22
90-60	90,000	60,000	20
105-85	105,000	85,000	17
120-100	120,000	100,000	14
150-125	150,000	125,000	9
175-145	175,000	145,000	6

The following ASTM specifications list steel castings for various purposes:

A128, Austenitic-Manganese Steel Castings
A217, Alloy-Steel Castings Suitable for Fusion Welding for High Temperature Service
A157, Alloy-Steel Castings for Valves, Flanges and Fittings for High Temperature Service
A148, Steel Castings, High-Strength for Structural Purposes
A296, Corrosion Resistant Iron-Chromium and Iron-Chromium-Nickel Alloy Castings for General Application
A297, Heat-Resistant Iron-Chromium and Iron-Chromium-Nickel Alloy Castings for General Application
A216, Carbon-Steel Castings Suitable for Fusion Welding for High Temperature Service
A27, Carbon-Steel Castings, Mild to Medium Strength, for General Application
A95, Carbon-Steel Castings for Valves, Flanges and Fittings for High Temperature Service
B190, Chromium-Nickel-Iron Alloy Castings for High Temperature Service
B207, Nickel-Chromium-Iron Alloy Castings for High Temperature Service

The Navy Department has the following specifications for steel castings:

49S1(INT)—Steel Castings
46S33—Steel—Alloy, Molybdenum Castings

The properties of cast steels are a function of their composition. Resistance to wear is obtained by the use of castings having a carbon content in excess of 0.40% and containing one of the following alloying elements: chromium, aluminum, nickel-chromium, chromium-vanadium and manganese. Corrosion-resisting properties are imparted to cast steels by alloying them with chromium and nickel and heat resistance up to 1000°F. by additions of chromium, tungsten, molybdenum and titanium. In general the weldability of cast steels is comparable to that of wrought steels with variations according to the chemical composition of the steel.

HOW TO WELD

Arc Welding

Ferritic Steels.—While it may be categorically stated that all cast ferritic steels are weldable, it must be acknowledged that the quality of the joint produced by arc welding may not be always satisfactory for the purpose intended. The possible deleterious thermal effects of welding can be avoided so that the weld metal will have mechanical properties comparable to the unaffected base metal by the use of proper welding procedures. For many cast steels the welding procedure would include preheat and postheat treatments. Sometimes a postheat treatment, such as normalizing or quenching and tempering, which is suitable for restoring the properties of the base metal in the heat-affected zone can adversely affect the weld metal, which, owing to its low-carbon content (usually 0.12% max.) may not respond to heat treatment.

In welding low-alloy steels, the general practice is to employ a filler metal having mechanical properties equal to those of the base metal regardless of differences in chemical composition. In addition to matching the mechanical properties of the weld and base metals at room temperature, it is often important, particularly for weldments intended for high temperature service, that properties affecting service at elevated temperatures such as coefficient of expansion, rupture strength and creep strength also be matched. To accomplish this it is often necessary to

use filler metal having a chemical composition very similar to the chemical composition of the base metal.

Welding techniques and procedures for manual, automatic and semi-automatic arc welding applicable to wrought steels also are applicable to cast steels. Selection of the filler metal as discussed above is a function of the intended service of the weldment, and also whether welding can be performed in the flat or in other welding positions, whether welding is to be done in deep or shallow grooves or fillet welds are to be used and whether the steel is subject to underbead cracking. Other considerations, such as poor fit-up, represented by loosely applied backing plate within a complex casting, also influence the selection of the filler metal used for the initial passes of the weld. The joint preparation and design for cast steels are in all respects suitable for welding wrought materials. Chamfering may be accomplished by chipping and machining, even grinding or oxygen cutting for low-carbon steels. Grinding or oxygen cutting on air-hardening steels is not advisable, even though preheating is applied prior to oxygen cutting. A higher carbon content usually will increase hardenability which as a rule requires an increase in the preheat level. Similarly the postheat treatment too may be modified either by increasing the postheat temperature over that used for the lower carbon material or by increasing the time of heat treatment and maintaining the temperature level. Proper procedures of preheating and post-heating may be determined empirically or by experience. A method of determining the applicable stress relief treatment, based on determination of the minimum temperature at which a heated beam under an applied static load suffers permanent deformation at an extreme fiber stress of 3000 psi., is given by B. Ronay (see Bibliography).

Austenitic Steels.—Austenitic steels are weldable by arc-welding procedures in the same manner as wrought ferritic steels. However, owing to the high coefficient of expansion of many of the chromium-nickel type austenitic steels, and the relatively low thermal conductivity of these materials, arc welding, particularly as it is applied in maintenance and salvage work of heavy sections, does not often result in the production of sound deposits. Owing to the above conditions, it is often necessary in welding heavy sections to depart from the usual procedure of employing filler metal of matching composition and employ electrodes depositing weld metal whose coefficient of expansion is at variance with that of the base metal to a degree sufficient to overcome the shortcomings.

Cast austenitic steels are generally employed for high temperature service and corrosion resistance. For this reason, selection of the filler metal is usually more critical than for welding ferritic steels, even though the latter are sometimes employed in high temperature service as in steam pipe lines. The properties of the austenitic steels, whether resistance to the erosion of high-temperature gases or the corrosive action of acids, are a function of their composition. Slight variations of the alloying elements in the weld metal from those of the base metal, usually permissible with ferritic materials, are seldom tolerated with austenitic steels. In other respects as in the selection of filler metal, joint design and preparation, as well as the welding techniques applicable to each electrode type or automatic or semi-automatic welding method, the welding procedures for cast steel are fully comparable to those employed in welding wrought steels of corresponding compositions (see Chapter 31A). While in general no preheating is required in welding the plain nickel-chromium type austenitic alloys, preheating is often beneficial and at times mandatory in welding the more complex types. The application of postheat treatment for austenitic weldments is not as common as for ferritic materials. Most austenitic materials, except those which develop their high temperature properties by precipitation hardening, are not subject to the structural changes which ferritic steels undergo during the welding cycle. For this reason, postheat treatment, which when applied to ferritic steels is intended, in part, to temper the hardening zone, is not justified. Postheat treatment at temperatures commonly used for ferritic steels to remove or reduce residual stresses is ineffective for most austenitic nickel-chromium steels, because the yield points of these steels are not considerably lowered at those temperature levels. When stress-relief heat treatment is desired and is applicable, the effective procedure for most nickel-chro-

mium austenitic steels is to heat to 2000°F. and quench. Obviously, this type of treatment is not suitable for localized applications.

Dissimilar Combinations.—Fabrication procedures often employ cast austenitic and ferritic steels in combination or cast austenitic materials combined with wrought ferritic steels. Each of these combinations represents an individual problem which must be evaluated employing such considerations and investigations as the character of the intended service warrants. Data are available concerning the successful welding and satisfactory service of weldments of the above types of combinations. The complexity of such welds as regards metallurgical and stress considerations renders a detailed discussion thereof beyond the scope of this chapter.

Austenitic Manganese Steels.—The physical properties of austenitic manganese steels (the so-called 14% manganese, Hadfield steels) are developed by a heat treatment consisting of quenching at about 1600°F. When this material is heated to or above the upper limit indicated for quenching, and is permitted to cool slowly at rates lower than that obtained in quenching, it becomes martensitic, a condition which renders it too brittle to be suitable for use for the applications for which it is intended in the austenitic form. Obviously, in arc welding, depending on the mass of the weldment, the desired quenching rate is not obtainable, and thus welding of these austenitic steels is problematical to a considerable extent. In the lighter gages, not exceeding 0.075 in., they can be welded obtaining reasonable joint efficiency and ductility at the fusion zones, employing either austenitic manganese or chromium-nickel-manganese (18–8–4) steel electrodes. When the thickness of the austenitic steel base metal exceeds 0.075 in., sound welds may be produced using the above type electrodes. However, the joint efficiency and the ductility are no longer comparable with those obtained for the lighter thicknesses. Manganese steel castings $^3/_8$-in. thick and heavier have been welded using the above type austenitic nickel-chromium electrodes in which on testing, failure occurs at the reduced tensile strength of the heat-affected zone.

Overlaying of cast manganese steel frogs and cross-overs is a standard procedure using austenitic manganese steel electrodes, often in bare wire form. The service itself furnishes work hardening, through which these materials develop mechanical properties comparable to those obtained through suitable heat treatment.

See Chapter 31B for further information on austenitic manganese steels.

Gas Welding

General.—Although metallurgical considerations permit the gas welding of all varieties of cast steels for which arc welding is applicable, the use of gas welding for cast steels is governed by economics, particularly for heavy sections. Another limiting factor is the necessity of applying a high degree of preheat which is difficult when welding heavy sections owing to the physical discomfort of the welder from exposure to the heat during welding. Gas welding of cast steels in thin sections, when economic considerations justify its use, is often done using the same type of weld preparation and technique as for gas welding wrought steels. The usual preparation for gas welding is the same as for cast iron, requiring a wider groove angle than that employed in arc welding, to permit free and unrestricted manipulation of the weld torch, particularly in depositing the root passes. As in welding cast iron it is advantageous to employ high velocity torch tips and use the backhand technique. However, unlike welding cast iron, cast steels are welded without the use of flux. The usual flame adjustment is neutral. As gas welding is applied at a slower rate of progression than arc welding the heat dwell is prolonged exaggerating metallurgical changes which occur at the fusion zones, particularly as regards grain growth. However, the same slower rate of progression and increased heat dwell are beneficial in some instances in that they reduce the cooling rate and prevent the development of underbead cracking. Gas welding, regardless of the lack of economical justification, is often applied to steels of excessive air hardening owing to elimination of the necessity for preheating whereby freedom from cracking is automatically assured. Gas welding is particularly applicable to such small castings as special fittings used in steam lines.

Ferritic Steels.—Gas welding is fully applicable for joining cast ferritic steels. However, economic considerations seldom justify its use except for thin sec-

tions. In addition to the economic factor there is the practical consideration of the inconvenience of the operation when applied to heavy sections and large masses of metal.

Austenitic Steels.—While gas welding of austenitic steels in the wrought state and in the form of light gage sheet or tubing is often done, it is seldom used for cast austenitic steels unless the thickness of the casting is very small. As mentioned above, the heat dwell in gas welding is rather extended and since a number of the chromium-nickel austenitic steels, even in the stabilized form, are prone to precipitate chromium carbides at the grain boundaries when they are exposed to the temperature range of 800 to 1200°F., gas welding, particularly of heavy sections, is not recommended when retention of the corrosion resistance of the heat-affected base metal is necessary.

Braze Welding.—Cast ferritic steels are frequently braze welded particularly as a maintenance or salvage operation. Braze welding is used for production in the fabrication of certain devices assembled from many intricate parts, such as pressure regulators for steam lines. The braze welding techniques for cast steel are the same as those used for cast iron except that edge preparation by grinding or oxygen cutting is satisfactory for cast steels having a carbon content of less than 0.35%. As with cast iron, a double-vee groove is preferred to facilitate maintenance of alignment, the groove angle being 90 to 120 deg. depending on the material thickness; the thicker the material the wider the angle.

The filler metal used is Naval brass, the same as for cast iron, with small additions of other elements to render it nonfuming. Preheating may often be restricted to the weld zone and the temperatures used are in the range of 800 to 900°F. Bulbous-type torch tips and a forehand technique are used. Welding can be done in all positions so that heavy frame members can be repaired without being dismantled. Deposition of the weld in layers not more than $^3/_8$-in. thick will assure freedom from porosity and will develop a grain structure beneficial toward maximum ductility and tensile strength of the weldment.

The joint efficiency of a braze-welded joint is relatively low; although the tensile strength of the deposited weld metal averages between 56,000 and 60,000 psi., its yield point is considerably lower than that of annealed mild steel. As with cast iron, braze welding of cast steel must be confined to applications where the joint is not exposed to atmospheric or electrolytic corrosion and where there is no possibility of failure due to thermal stresses resulting from the significant difference between the coefficient of expansion of the copper-base welding rod and the ferritic steel base metal.

Flash Welding

Mild, medium-carbon and some of the low-alloy cast steels, whose air-hardening tendency is not excessive, can be flash welded effectively. The more complex alloy steels, particularly those which are highly air hardening, offer certain difficulties in that the zone of fusion in these materials is not amenable to heat treatment, thus rendering such weldments unsuitable for applications subject to cyclic loading at stress levels which may exceed the fatigue value of the weakened weld zone. (Flash welding is described in detail in Chapter 17.) Preparation for flash welding may be by oxygen cutting, executed with the maximum accuracy applicable. The preferred method of preparation is machining. When the members to be joined are mounted on the machine, the two surfaces opposite one another are parallel within a reasonable accuracy of scale dimensions. In designing machine parts to be joined by flash welding, care must be taken to allow for the amount to be flashed off. This amount is variable, being a function in part of the cross-sectional area, the available power input and the composition of the steel. While data are available concerning the lengths required for flashing off for various cross-sectional areas, the optimum is best determined by empirical means or experiment for each application.

The metallurgical changes occurring in the weld zones of the flash-welded joint are comparable to those which occur in arc welding, except that the heat effect, owing to the longer current dwell, is exaggerated as regards grain growth and extent of heat-affected zone. As previously indicated, postheat treatment, which might be of a localized nature as in welded pipe joints, may be applied to eradicate the effects of the thermal cycle of flash welding and restore the heat-affected zone

to a grain structure comparable to that of the unaffected portions of the assembly. However, such treatments are not effective for the more complex compositions.

As flash welding is most suitable for structures of simple geometry such as tubes, rounds and squares, it is not readily adaptable for assembling castings whose contours are intricate and include abrupt changes of crosssection or other forms of unsymmetrical mass distribution. These considerations also render flash welding unsuitable for joining members of unequal cross-sectional area when the ratio of the two cross sections is large in that the energy input required to heat the heavier member of the joint may be excessive for the thinner member and beyond the capacity of the control apparatus to compensate for the higher rate of flashing-off of the thinner member.

Pressure Gas Welding

This process is occasionally used in the welding of steel castings. See Chapter 7 for further information.

Brazing

Cast steel is commonly furnace brazed. This process is particularly suitable for mass production. It is performed in specially constructed furnaces designed either for batch operation or for continuous operation using conveyors. Copper or copper-base brazing alloys are used. The furnaces provide a controlled atmosphere of hydrogen or hydrogen-enriched fuel gas mixture. The brazing temperature usually is from 2000 to 2100°F. Since the operation is performed in a controlled atmosphere, no flux is required, and the brazed products emerge free from oxidation. Preparation for furnace brazing requires suitable fits for the intended joints. Depending on the nature of the application, the joint may be assembled with a press fit or it may have a clearance of a few thousandths of an inch. The brazing alloy, depending on the joint design and the location of the joint, may be applied in the shape of thin washers or sheets or in the form of wire or powder. Cast steels are being joined with silver brazing alloys, usually those having flow points not over 1200°F. Preparation for brazing with silver alloys usually requires clearances of 0.003 to 0.007 inch. The gap usually increases with the mass of the objects being brazed. For this type of brazing the use of proper fluxes is mandatory. These alloys can be used in torch brazing, furnace brazing, resistance brazing or induction brazing. Induction brazing is particularly suitable for production work, partly because it permits a fast rate of production and provides a very ready means of temperature control, and therefore produces joints of comparable uniform quality. The brazing material for this process is applied in sheet or wire form. The capillary forces of these brazing alloys is not as positive as that of the higher-melting-point copper or copper alloys used in furnace brazing and therefore more care must be used in placing the brazing alloys. For each application pilot tests should be performed to determine the optimum location and volume of the brazing alloy to be applied. The efficiency of joints produced by silver brazing alloys is usually computed on the basis of 30,000 psi. in shear, which is usually the only recommended method of loading joints united by the use of silver brazing alloys. Brazed weldments using the above types of brazing alloy are suitable for service at temperatures not exceeding 500°F. In many applications the joint design requires that the brazing alloy form a fillet in order to prevent sharp change of cross section; if such fillets are exposed to liquids which may become electrolytes in the presence of the ferrous base metal and the brazing compound the possibility of corrosion is introduced. (See Chapter *22* for further information on brazing.)

Thermit Welding

The application of thermit welding to cast steels in most respects is comparable to its use in the welding of cast iron. In general, the necessity of preheating parts which may restrict free shrinkage of the weld also exists. However with cast steels, in many instances expansion of the restricted parts can be obtained by straining the metal mechanically owing to the high ductility of cast steels. Thermit mixtures are available to yield weld metal whose mechanical properties match or closely approximate those of the base metal, although the chemical composition of the weld metal may differ from that of the base metal. Generally, this process is employed for welding cast steel machinery frames and other comparably heavy structures.

Processes Not Applicable

With the exception of valves whose intricacy of design permits more economical production by casting than by other methods of fabrication, the use of steel castings is restricted to structures $^1/_8$ in. or thicker in section. For this reason, welding processes which may be preferred for welding steels in thin sections, such as atomic hydrogen welding or seam welding, are not generally applicable. In the construction of some intricate machine parts, such as turbine casings, cast and wrought sections are united by manual arc welding or by any of the automatic arc-welding processes, but in general these automatic processes are not used because the cost of preparation for welding for most assemblies would render their use uneconomical. The bulk and shape of castings generally do not permit the use of resistance welding for affixing attachments or other similar applications. Inert-gas metal-arc welding, which is particularly suitable for welding austenitic steels in light gages, has not found any application as yet in salvaging and finishing castings.

COMMON APPLICATIONS

Cast steel is still an important element in both power-plant equipment and machinery fabrication. Valves for use in steam lines and in oil refineries are made of cast steel whose composition ranges from mild steel to complex austenitic materials. Cast steel is used for the turbine casings and the valve chests of steam turbines. Hydraulic turbines and their impellers are also steel castings, as are the frames of electric motors and generators, also the subbases for mounting electric motors and the other prime movers. The frames and cylinders of the modern high-powered locomotives are also steel castings. The process industries use cast steel autoclaves and other heat exchangers intended for high temperature, high pressure service. Other uses of steel castings are trunnions and other parts of foundry ladles and other heavy industrial equipment such as earth-moving machinery and parts of suspension bridges. Cast steel is used in heavy ordnance and for ship structures such as stern posts and rudder frames.

BIBLIOGRAPHY

A. Cast Iron

1. *Alloys of Iron and Silicon,* G. S. Greiner, J. S. Marsh and Bradley Soughton, McGraw-Hill Book Co., 1933.
2. *The Microscope in Elementary Cast Iron Metallurgy,* R. M. Allen, American Foundrymen's Association, 1939.
3. *Procedures for Arc Welding Gray Iron Castings,* C. E. Phillips, The Welding Journal, June 1946.
4. *Welding of Heavy Gray Iron Castings,* L. J. Larson, The Welding Journal, June 1947.
5. *Welding Techniques for Cast Iron,* T. E. Kihlgren, The Welding Journal, January 1948.
6. *Recommended Practices for Salvaging Automotive Gray Iron Castings,* Committee Report, The Welding Journal, May 1948.
7. *Stress-Corrosion in Naval Brass,* B. Ronay, The Welding Journal, April 1949.
8. *Nickel Topics,* published monthly by International Nickel Co.

B. Cast Steel

1. *Symposium on Effect of Temperatures on Metals,* American Society for Testing Materials and the American Society of Mechanical Engineers, 1931.
2. *Steel Castings Handbook,* Steel Founders Society, 1941.
3. *Metallurgy of Steel Castings,* C. W. Briggs, McGraw-Hill Book Co., 1946.
4. *Susceptibility of Cast Steels to Graphitization,* J. J. Kanter, The Welding Journal Res. Suppl., Feb. 1947.
5. *The Welding of Cast Steels—General Specifications for Inspection of Material, Appendix VII—Welding, Part C, Section C-3,* Navy Department, Washington, D. C.

CHAPTER 29

LOW ALLOY STEELS*

GENERAL PROPERTIES

Classification

Alloy steels are those steels which have special properties attributable to the presence of one or more elements in addition to those commonly present in carbon steel or to greater than usual proportions of such elements as manganese or silicon (see Tables 3 and 4). No rigid classification of low-alloy steels has been accepted. The same steel may be considered as low, medium or high in alloy by different users.

This chapter covers the constructional steels ranging in composition between plain-carbon and manganese steels (Chapter 27) and chromium irons and steels (Chapter 30). This includes the so-called high-strength, low-alloy group of proprietary steels which is generally intended for use in the hot-rolled condition and the large group of wrought low-alloy steels which is available commercially for the manufacture of heat-treated parts. It should be noted that there is overlapping in composition range between these two groups, and that the high-strength, low-alloy grades may have higher alloy contents than steels which have superior strength in the heat-treated condition.

Hot-Rolled Grades

Specifications.—Since early in the century, various efforts have been made to promote the use of nickel-, manganese- and silicon-alloyed hot-rolled steels. Not until 1933 was a sufficient demand for improved strength and corrosion resistance developed by the transportation industry to initiate the large-scale production of what is now known as the high-strength, low-alloy group of steels. These steels are supplied to minimum mechanical properties and are usually furnished in the hot-rolled condition. They are normally intended for use without further heat treatment, and during welding no preheat or postheat is required. Stress relief may sometimes be prescribed for welded structures of the hot-rolled grades.

High-strength, low-alloy, hot-rolled steels are covered by the *Recommended Practice for SAE 950 Steel* in the 1949 SAE Handbook. Chemistry limitations are as follows: For resistance welding, 0.12% maximum carbon and 1.00% maximum manganese; for other than resistance welding and non-welded applications, 0.20% maximum carbon, 1.25% maximum manganese, 0.050% maximum sulfur, 0.15% maximum phosphorus, 0.90% maximum silicon. Other alloys and their ranges are subject to agreement between the purchaser and producer.

Minimum tensile properties vary with the plate thickness from 50,000 psi. yield strength, 70,000 psi. tensile strength, and 20% elongation in 2 in. for $^1/_2$ in. or lesser thickness to 45,000 psi. yield strength, 65,000 psi. tensile strength, and 22% elongation for 1 to 2 in. thick. A 180 deg. bend test on the plate thickness for gages up to $^1/_2$ in., on twice the plate thickness for gages from $^1/_2$ to 1 in., and on three times the plate thickness for between 1 and 2 in. is required. Various users and government agencies have included weldability or simulated welding tests in individual specifications, but no wide agreement as to types of tests or specific requirements for weldable high-strength steel has been reached.

Mechanical Properties.—Ordinary struc-

* Prepared by a committee consisting of S. A. Herres, Allegheny Ludlum Steel Corp., *Chairman;* T. N. Armstrong, International Nickel Co.; H. M. Banta, Battelle Memorial Institute; J. J. Chyle, A. O. Smith Corp.; Howard Cross, Battelle Memorial Inst.; L. A. Danse, General Motors Corp.; J. R. Dawson, Union Carbide & Carbon Res. Labs.; R. F. Miller, Carnegie Illinois Steel Corp.; A. Muller, Air Reduction Sales Co.; G. C. Riegel, Caterpillar Tractor Co.; A. J. Williamson, Summerill Tubing Division of Columbia Steel and Shafting Co.

tural plain-carbon or mild steel of 0.20% carbon, 0.15% silicon and 0.50% manganese has a tensile strength of 50,000 to 65,000 psi. and a yield strength of 25,000 to 30,000 psi. in the hot-rolled condition. The most inexpensive means of increasing the strength is to increase the carbon content, but this is accompanied by loss in ductility and toughness, and in the qualities desired for commercial fabrication, particularly weldability. For example, a 0.40% carbon steel has a tensile strength of 75,000 to 85,000 psi. and a yield strength of 35,000 to 40,000 psi., but cannot be satisfactorily welded under so broad a range of conditions as lower carbon steels.

Strong hot-rolled steels of medium carbon and with manganese in the range of 1.0 to 1.75% were used for many years in riveted constructions where little cold forming was required, but these steels are generally unsuitable for welded construction because of their tendency to

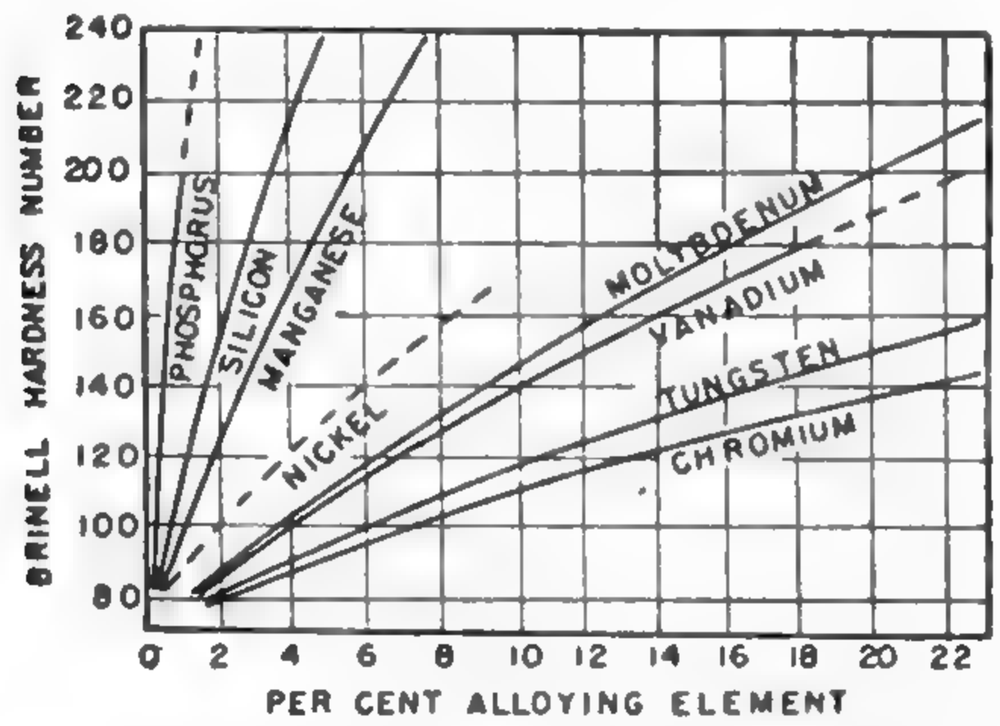

Fig. 1.—Probable Hardening Effects of the Various Elements as Dissolved in Pure Iron

crack in the weld or the heat-affected zone. To overcome this difficulty, welding-grade, hot-rolled steels were made with lower carbon, with alloying elements other than high manganese alone added to obtain high strength, and with aluminum, vanadium or titanium additions to obtain fine grain, higher yield to tensile strength ratios and better notched-bar impact toughness.

The over-all effects of alloying additions to low-carbon steels are the sum of relatively small strengthening from solid solution of the alloys in iron and the hardening produced as a result of the changes in the type and distribution of the carbides and from precipitation hardening. The same effects can be obtained by using alloying elements in different amounts and various combinations. The comparative effects of some alloy elements in hardening of pure iron are illustrated by Bain (Fig. 1). The differences in hardness caused by alloying elements are small in comparison to the hardening produced by changes in the type and distribution of carbides present (Fig. 2). Even

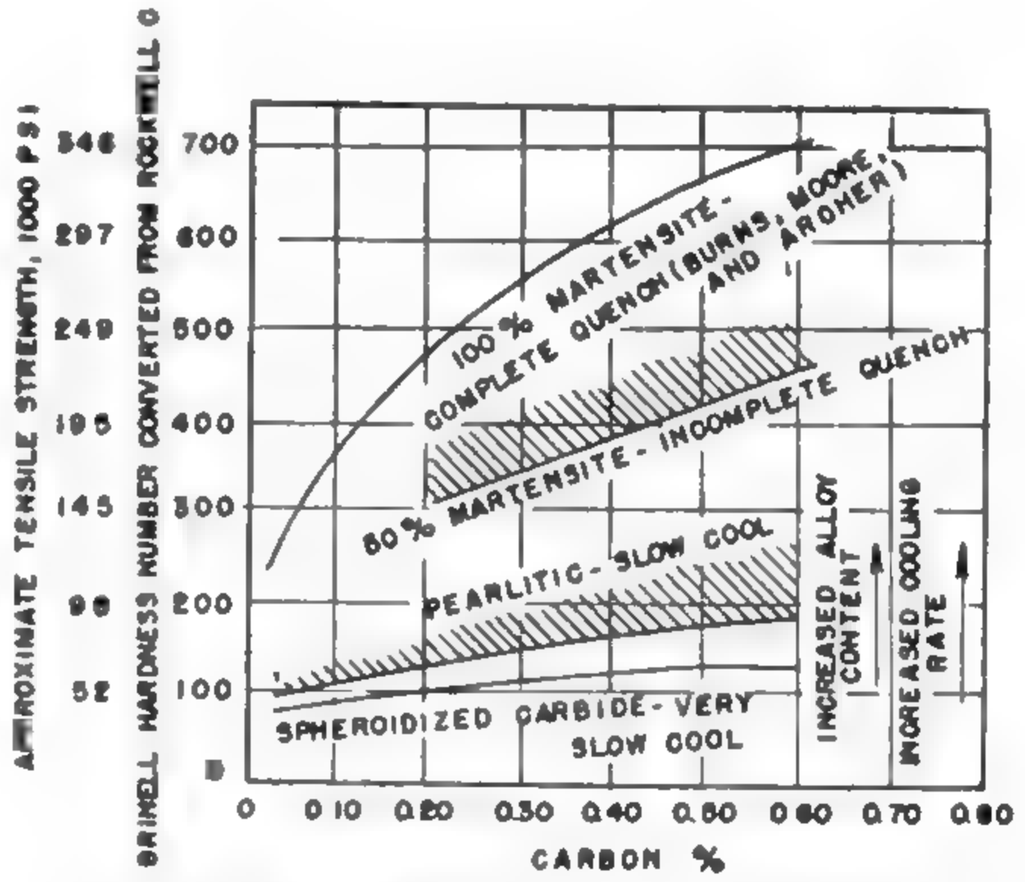

Fig. 2.—Approximate Tensile Strength Obtainable for Steels in Various Heat-Treated Conditions as a Function of Carbon Content

in low-carbon, hot-rolled steels the major importance of alloy additions probably is attached to this influence on carbides.

The approximate tensile strength of hot-rolled steels as influenced by variations in chemical analysis and plate thickness may be estimated from the formula of Quest and Washburn, given in Table 1. By maintaining a relatively low carbon content and introducing alloying elements, an increase in strength proportionate to

Table 1—Strength of Hot-Rolled Steel

$$\text{T.S. (psi.)} = 38{,}000 + C\,(700 + 2.94\,Mn) + Mn\left[30 + \frac{Mn}{200}\,(48 + 2.35\,C)\right] + P\,(1000) + Si\,(340) + K$$

C, Mn, P and Si are included as *points* (0.01% = 1 point) of these elements

K is a gage factor = −3000 for 0.75 in. and up
−2000 for 0.625 in.
−1000 for 0.500 in.
0 for 0.375 in.
+1000 for 0.250 in.
+2000 for 0.125 in.

This formula is accurate to ±5000 psi. on ladle analyses and 50% better on check analyses. The range covered is C 0.10–0.35%, Mn 0.30–1.60%, P 0.01–0.04% and Si 0.01–0.15%. Other elements increase the T.S. as follows in psi. for each 0.01 %; Cu 400, Ni 250, Cr 60–200 (depending on the percentage of C), Sn 1000.

that in higher carbon steels is obtained without a sacrifice of ductility or welding quality. French has illustrated the influence on tensile properties of several alloy elements (Fig. 3).

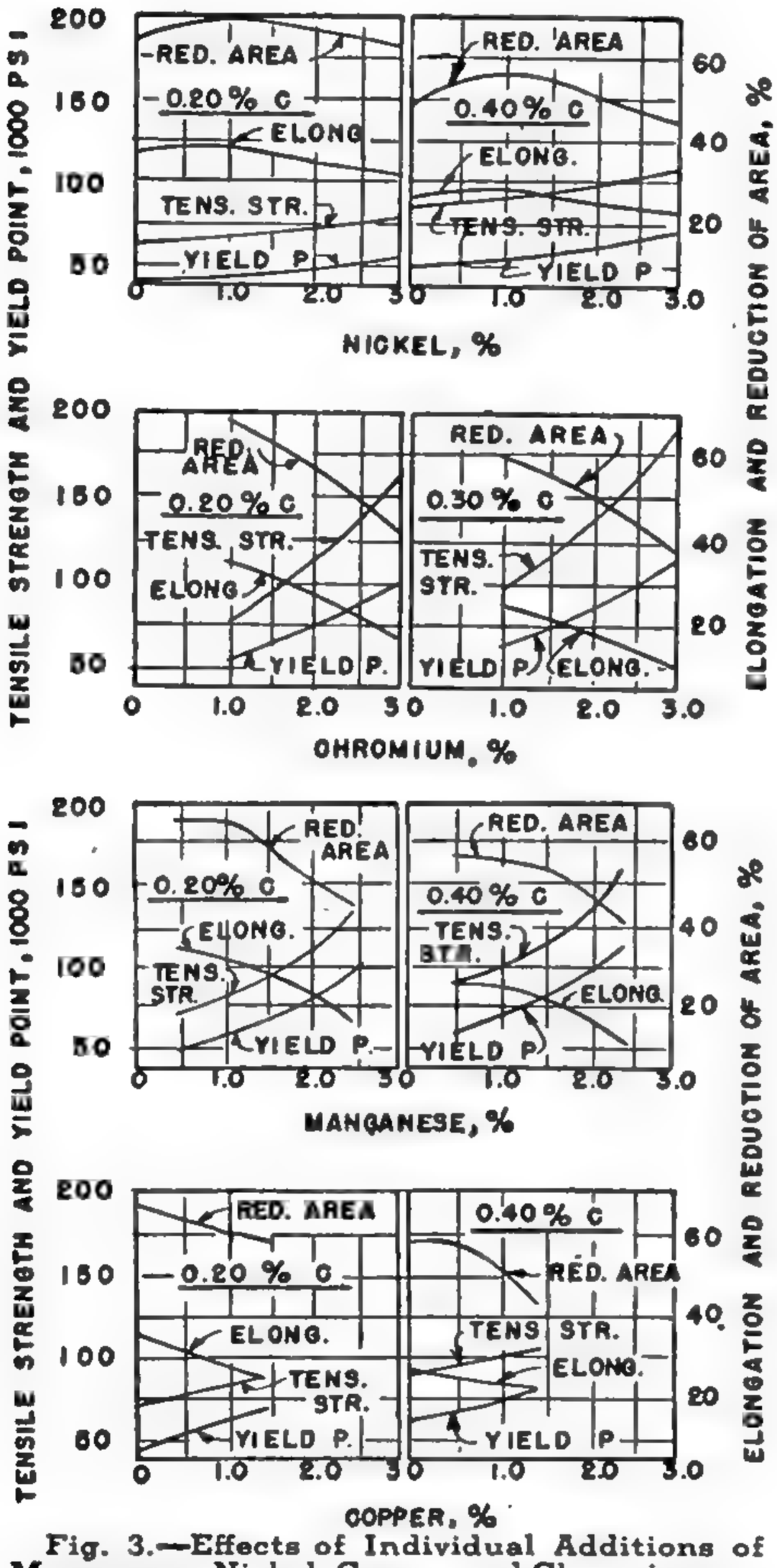

Fig. 3.—Effects of Individual Additions of Manganese, Nickel, Copper and Chromium on the Tensile Properties of Normalized Steels

Although yield strength is proportionate to tensile strength in fully quenched and tempered steels, the proportionality does not hold in hot-rolled or normalized steels. Kramer, Gorsuch, and Newhouse found that the order of potency for increasing the tensile strength of air-cooled, $^{4}/_{4}$-in. rounds is P, Mo, Mn, Cr, Si, Cu and Ni, but the yield ratio is increased most by small additions of the grain-refining agents, Al, V, Ti and Zr followed in order by Cu, Mn, Ni, Si, Cr, P and Mo. These observations are qualitatively consistent with the general choices of alloying elements for low-alloy, hot-rolled steels.

The two elements, phosphorus and copper, are little used in heat-treated steels but find considerable use in hot-rolled steels. Phosphorus is the most effective of the ferrite strengtheners and is also helpful in retarding atmospheric corrosion. The high-phosphorus steels contain more than the usual specification limit of 0.04% phosphorus in addition to copper and one or two other alloy elements. Phosphorus is usually in the range of 0.07 to 0.15%.

Phosphorus tends to segregate in the steel ingot and persists as a banded structure that is not readily broken up by rolling of the plate. Therefore, phosphorus must be held down so that the segregated areas will not be too high in phosphorus. Welding difficulties are minimized by holding carbon below 0.15% with 0.07 to 0.12% phosphorus. Notched-bar impact resistance, particularly below room temperature, drops as either the carbon or the phosphorus content increases. A sum of 0.25% of carbon plus phosphorus is generally recognized as the upper limit of safety for good shock resistance in structural steels. However, the use of aluminum for grain-size control and the addition of other alloy elements, particularly molybdenum and chromium, appear to diminish the tendency for embrittlement of phosphorus-containing steels. The polished-bar endurance limit of these phosphorus-containing steels appears to be high, considerably above the usual ratio of from 40 to 50% of the tensile strength.

Copper improves the resistance to atmospheric corrosion and has a moderate influence in contributing to ferrite strengthening and quench hardenability. Copper in amounts of 0.5 to 1.5% is also capable of providing increased strength to mild alloy steels by a precipitation-hardening process. The copper is held in solution in these steels by ordinary air cooling without drastic quenching, and the full precipitation-hardening effect is, therefore, realized on reheating hot-rolled or normalized steels to the precipitation temperature. The amount of hardening on reheating increases as the copper content is increased from 0.5 to about 1.5%, but appears to decrease with further in-

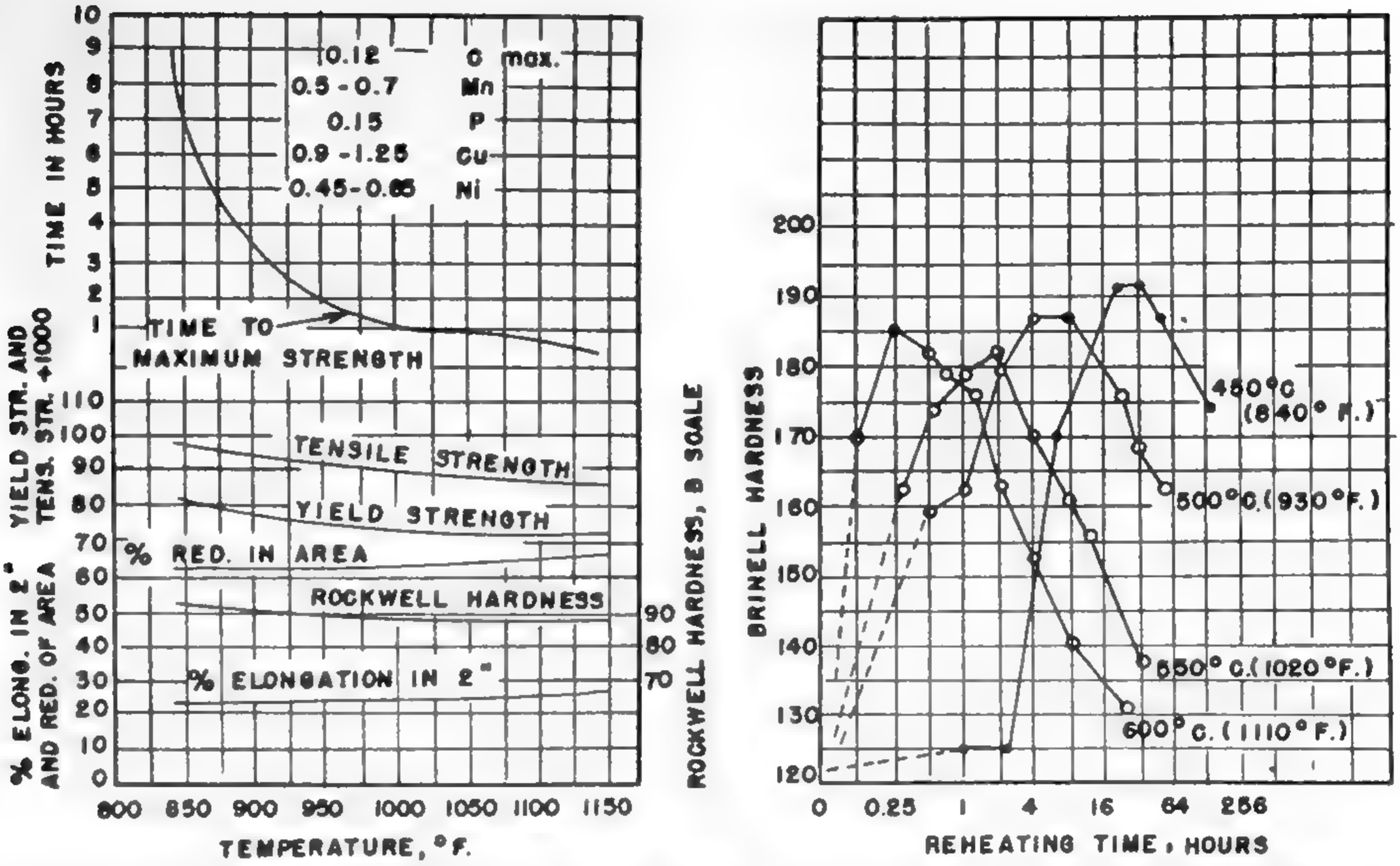

Fig. 4.—Influence of Reheating on Mechanical Properties of Copper-Containing Steels

crease in copper. Figure 4 gives some data on time-temperature relationships for precipitation hardening of two steels.

The presence of other alloys has relatively little effect on the course of the precipitation-hardening effect, and the reheating of copper-bearing, hot-rolled steels for a suitable time interval at the appropriate temperature permits an increase of 10,000 to 20,000 psi. in tensile strength. This treatment often is combined with a postwelding stress-relief heat treatment. However, the times and temperatures for adequate thermal stress relief of welded structures are somewhat greater than those for maximum copper precipitation hardening. Also, the increase in strength by precipitation hardening is usually accompanied by a decrease in notched-bar impact resistance. If phosphorus and silicon are held low and the steel is aluminum killed and alloyed with molybdenum, the notched-bar impact resistance after strengthening by precipitation hardening may still be sufficiently high for most structural purposes. Table 2 gives some illustrative strength and toughness data.

Table 2—Mechanical Properties of Copper-Bearing Steels (1/2-In. Thick)

Heat Treatment	Yield Strength, 0.1% Psi.	Tensile Strength[a], Psi.	Percent Elongation in 2 In.	Charpy V-Notch[b], Ft.-Lb. at: +70° F	−40° F.	−100° F.
		Commercial Cu-Ni-P				
	0.09%C, 0.71%Mn, 0.06%Si, 0.025%S, 0.12%P, 0.55%Ni, 1.05%Cu					
Hot rolled	65,600	71,300	37.5	18	....	....
900° F., 4 hrs.	72,800	93,500	30.0	2 3	....	....
1150° F., 6 hrs.	51,600	71,000	35.0	5 6	....	....
		Commercial Ni-Cu-Mo				
	0.17%C, 0.79%Mn, 0.01%Si, 0.03%S, 0.015%P, 1.11%Ni, 0.62%Cu, 0.24%Mo					
Hot rolled	58,400	95,000	23.0	29-31	12-21	....
900° F., 4 hr.	73,600	103,600	23.0	25-22	6-12	....
1150° F., 6 hr.	60,000	91,200	28.5	34-36	8-12	....
		Experimental Mn-Ni-Cu-Mo				
	0.11%C, 1.04%Mn, 0.09%Si, 0.019%S, 0.008%P, 0.38%Ni, 0.70%Cu, 0.53%Mo, Al-killed					
1550° F., normalized	45,500	76,500	29.5	60-62	27-29	....
900° F., 4 hr.	64,000	86,000	28.0	35-36	....	....
1150° F., 6 hr.	57,200	73,200	33.0	57-56	24-25	16-15

[a] Flat plate tensile specimen parallel to direction of rolling.
[b] Specimen transverse to direction of rolling, notch perpendicular to plate surface.

Table 3—Representative High-Strength, Low-Alloy Steels

Data given, except for noted exceptions, are for plate 1/2 in. thick in the hot-rolled condition

Brand Name	Composition, %											Yield Point, Min., Psi.	Tensile Strength, Min., Psi.	Elongation, Min. %	Producer
	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Zr	Al				
Aldecor	0.12 max.	0.15–0.40	0.08–0.15	0.05 max.	0.35–0.75	0.35–0.60	.....	.....	0.16–0.28	.....	.....	50,000	70,000	22[a]	Republic Steel Corp.
Double Strength	0.12 max.	0.50–1.00	0.04 max.	0.05 max.	.....	0.50–1.00	0.50–1.10	.....	0.10 min.	.....	.....	50,000	70,000	22[a]	Republic Steel Corp.
Dynalloy	0.20 max.	1.25 max.	0.100 max.	0.05 max.	0.30 max.	0.60 max.	1.00 max.	.....	0.10 max.	.....	.....	50,000	65,000–80,000	[b, d]	Alan Wood Steel Co.
	0.12 avg.	0.75 avg.	0.080 avg.	0.035 avg.	0.05 avg.	0.40 avg.	0.60 avg.	.....	0.08 avg.	.....	.....	.....	.....	...	
Hi-Steel	0.12 max.	0.50–0.90	0.05–0.12	0.05 max.	0.15 max.	0.95–1.30	0.45–0.75	.....	0.08–0.18	.....	0.12–0.27	50,000	70,000	[b, c]	Inland Steel Co.
Manganese-Nickel-Copper	0.25 max.	1.40 max.	0.045 max.	0.05 max.	0.25 max.	0.30–0.60	0.50–1.00	.....	.....	.....	.....	50,000	70,000	[b, c]	Carnegie-Illinois Steel Corp.
Mayari-R	0.12 max.	0.50–1.00	0.08–0.12	0.05 max.	0.10–0.50	0.50–0.70	0.25–0.75	0.40–1.00	.....	.....	.....	50,000	70,000	[b, c]	Bethlehem Steel Co.
N-A-X High Tensile	0.08–0.15	0.50–0.75	0.04 max.	0.05 max.	0.60–0.90	Resid.	Resid.	0.50–0.65	.....	0.05–0.15	.....	50,000	70,000	[c]	Great Lakes Steel Corp.
Otiscoloy	0.15 max.	0.90–1.40	0.08–0.13	0.04 max.	0.10 max.	0.30 min.	Resid.	Resid.	.....	.....	.....	50,000	70,000	25[a, d]	Jones and Laughlin Steel Corp.
Yoloy	0.15 max.	0.60 max.	0.05–0.10	0.05 max.	.....	0.75–1.25	1.50–2.00	.....	.....	.....	.....	50,000	70,000	22[a]	Youngstown Sheet and Tube Co.
Cor-Ten	0.12 max.	0.20–0.50	0.07–0.15	0.05 max.	0.25–0.75	0.25–0.55	0.65 max.	0.50–1.25	.....	.....	.....	50,000	70,000	[b, c]	Carnegie-Illinois Steel Corp. Tennessee Coal, Iron and Railroad Co. Geneva Steel Co. American Steel and Wire Co. Republic Steel Corp.

NOTE: All of these steels, in thicknesses up to and including 1/2 in., are capable of at least meeting ASTM Standard Specimen cold bend of 180 deg. over a diameter equal to the thickness of the material.

[a] Percent elongation in 2 in., ASTM Standard Flat Specimen.

[b] 1,500,000/T.S. = minimum percent elongation in 8 in., ASTM standard Flat Specimen.

[c] For thicknesses under 3/16 in., 22% minimum elongation in 2 in., ASTM Standard Sheet Specimen.

[d] For thicknesses under 3/16 in., 25% minimum elongation in 2 in., ASTM Standard Sheet Specimen.

[e] Typical value for 1/2 in.-plate, 27% in 8 in., ASTM Standard Flat Specimen.

Copper in amounts above about 0.25% tends to cause surface cracking during hot working of steels. This is prevented by an addition of nickel in a proportion of approximately one-half that of the copper content. The first important copper-alloyed wrought steels contained 2% Ni and 1% Cu. During the war when nickel was short, the copper-nickel ratios of large-tonnage copper-alloyed steels ranged between 0.5% Ni to 1.0% Cu and 1.6% Ni to 0.80% Cu.

Several early hot-rolled steels were alloyed with silicon. Mill difficulties and a tendency toward brittleness have discouraged the use of high silicon. However, silicon of less than 1% is used as an alloying element in several of the low-alloy, hot-rolled steels.

Chromium in amounts of 0.25 to 1.25% and molybdenum at 0.10 to 0.25% are frequently used in conjunction with the high-phosphorus or the copper-nickel combination. Deoxidation and grain-size control when required are ordinarily accomplished by a small (0.05 to 0.15%) aluminum addition. Vanadium and/or titanium have been used for grain-size control, particularly in manganese alloyed steels such as the *Man Van* and the more recent *Vanity* steels. The latter type now tends toward 0.16 to 0.18% C, 1.10 to 1.30% Mn, 0.20 to 0.30% Si, 0.05% V, 0.02% Ti, 0.02% Al with residuals of 0.05 to 0.40% Cu, 0.10 to 0.20% Ni, 0.05% Cr and intentional molybdenum additions up to 0.15% in the heavier gages. The *Vanity* type steels played an important role in critical ship structures where 48,000 psi. minimum yield strength was required.

Table 3 gives a list of representative proprietary high-strength, hot-rolled steels. In $^1/_2$-in. or lesser gages, each of these steels may be expected to have a minimum yield strength of 50,000 psi., and a tensile strength between 65,000 and 75,000 psi. Tensile elongation of flat plate specimens will exceed 20%. Cold finishing may be required in the rolling of *Dynalloy* to obtain 50,000 psi. yield strength.

Heat-Treated Grades

Specifications.—A large variety of chemical compositions is available commercially for the user of heat-treatable steels. Authoritative specifications are provided by the Society of Automotive Engineers (SAE steels) and by the American Iron and Steel Institute (AISI steels).

These specifications define limits of variation of the principal alloy elements and impurities in the steels and, in some instances, the methods of manufacture. The AISI and SAE steel classifications have identical numbers and specified ranges of chemical composition although the AISI steels cover more grades. Table 4 includes the principal type compositions of AISI and SAE Steel specifications.

Table 4—Principal Type Compositions for AISI and SAE Steel Specifications[a]

10xx	Carbon steels
11xx	Free-cutting resulfurized C-Mn steels
13xx	1.75% manganese steels
23xx	3.5% nickel steels
25xx	5.0% nickel steels
31xx	1.25% Ni, 0.6% Cr steels
33xx	3.50% Ni, 1.5% Cr steels
40xx	0.25% molybdenum steels
41xx	0.25% Mo, 1.0% Cr steels
43xx	0.25% Mo, 1.75% Ni, 0.50% Cr steels
46xx	0.25% Mo, 1.75% Ni steels
48xx	0.25% Mo, 3.5% Ni steels
50xx	Low-chromium (0.75% max.) steels
51xx	Medium-Cr (1.20% max.) steels
52xxx	High-C, medium-Cr (1.6% max.) steels
61xx	1.0% Cr, 0.15% V steels
86xx	0.55% Ni, 0.50% Cr, 0.20% Mo steels
87xx	0.55% Ni, 0.50% Cr, 0.25% Mo steels
92xx	0.80% Mn, 2.0% Si (may contain Cr)
93xx	3.25% Ni, 1.20% Cr, 0.12% Mo steels
94xx	0.45% Ni, 0.40% Cr, 0.12% Mo steels
97xx	0.60% Ni, 0.17% Cr, 0.20% Mo steels
98xx	1.0% Ni, 0.80% Cr, 0.25% Mo steels

[a] Approximate and incomplete; consult AISI and SAE steel specification lists for standard ranges and limits, which are subject to periodic revisions.

In general, the last two digits of a four-numeral series or the last three digits of a five-numeral system represent the average carbon content in one-hundredths of 1%, i.e., xx40 represents a range of 0.38 to 0.43% carbon, but the exact range varies with the type steel and, in some instances, variation in the last digit may indicate differences in the ranges for manganese, phosphorus, sulfur or other elements.

In the AISI system, when there is no prefix the steel is predominantly basic open hearth, the prefix *B* represents Bessemer, and *E* electric-furnace steels. The usual range of silicon in open-hearth alloy steels is 0.20 to 0.35%, and sulfur and phosphorus have 0.04% maximums. Bessemer steels usually are slightly higher in phosphorus and sulfur content,

and steels specified as electric furnace usually are below 0.025% in phosphorus and sulfur.

Recently, cooperative work of the Iron and Steel Committee of the War Engineering Board, Society of Automotive Engineers, and American Iron and Steel Institute has resulted in a new type of specification for constructional steels. This applies to steels produced to hardenability bands determined by the standard end-quench test on 1-in. round bars. These steels are identified by the suffix letter *H* added to the AISI or SAE series number. The chemical composition ranges for *H* steels are modified to permit selection by desired hardenability rather than by chemical composition.

The variation between the hardenabilities of two heats, both meeting the old chemical specifications but one with all elements on the high side and the other with all elements on the low side, is greater than for a corresponding *H* steel. Since too low hardenability may adversely affect mechanical properties, and high hardenability increases tendency toward weld or quench cracking, the user of alloy steels in welded structures should become familiar with the hardenability specification system.

Neither SAE nor AISI steel specifications refer to the manganese-molybdenum alloy steels which were used in large tonnages for welding armored vehicles during the war. Nor do the present specifications cover boron-treated steels. The use of boron-containing addition agents, which introduce about 0.003% or less boron and markedly increase hardenability, was widely practiced to conserve other alloy elements during the war.

Mechanical Properties.—The dependence of mechanical properties on the heat treatment and chemical composition of alloy steels may be shown by a few simple illustrations. As indicated in Fig. 2, the maximum hardness attainable by heat treatment in any low-alloy steel depends exclusively upon the carbon content. Hardening is accomplished by heating the steel above the critical transformation temperature where the steel undergoes a lattice change and takes carbon into solid solution (austenite structure). At normal temperatures, carbon has very limited solubility in low-alloy steels. Slow cooling of austenite rejects the carbon as relatively large platelets of iron carbide (pearlite structure). Rapid cooling produces an extremely fine dispersion of carbon (martensite structure) and high hardness. Intermediate cooling rates produce bainitic structures or mixed structures of intermediate hardnesses.

In sufficiently small sections, plain-carbon steels may be cooled rapidly enough by water quenching to give a fully-hardened structure. The principal function of alloying elements is to in-

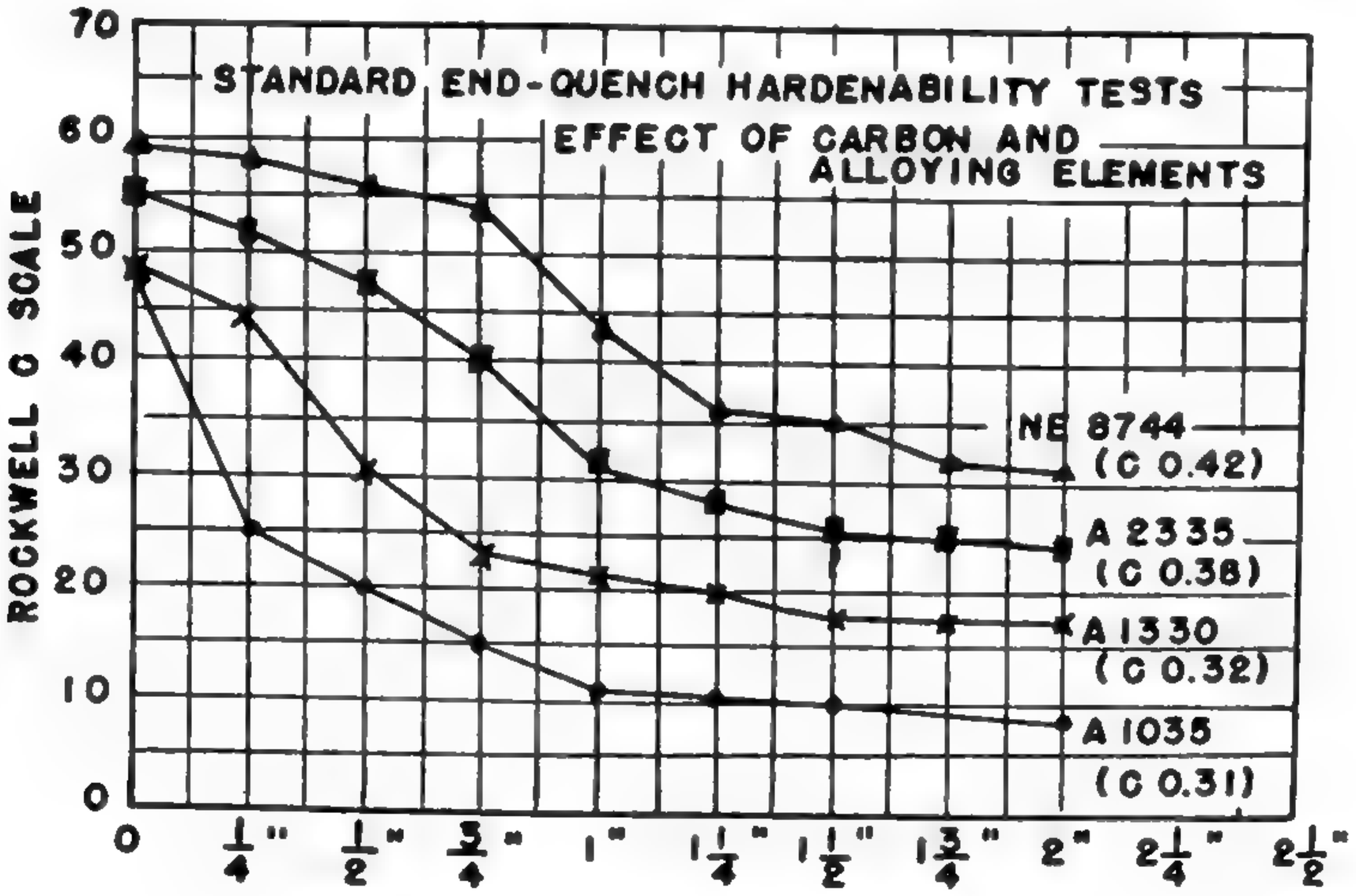

Fig. 5.—Effects of Carbon and Alloying Elements on Hardenability

crease the depth of hardening or size of section that may be fully hardened by quenching.

Figure 5 shows standard end-quench hardenability test results for four steels. The maximum hardness at the water-quenched end depends upon the carbon content, but the depth of hardening is seen to depend upon the alloy content. It is known that properly selected combinations of elements are more effective in increasing hardenability than a larger quantity of a single element. The hardenability problem is complicated by the fact that individual alloys vary in their ability to prevent transformation to pearlitic or bainitic structures, and at a given percentage their action varies according to the kind and amount of other alloying elements present. There are several systems for estimating the approximate effect of the various elements on hardenability.

During tempering, the steel softens at a rate which depends somewhat on the individual alloying elements present. Figure 6 shows some examples. The two 0.20% carbon (*) steels were obviously not fully hardened by quenching prior to tempering. In fact, recent studies indicate that none of these low-alloy steels will be fully hardened to martensite to the center of a 1-in. round when quenched in oil or water.

One of the most important principles realized in recent years is that when low-alloy steels are fully hardened by quenching and tempered to any stated hardness below about 500 Brinell, the mechanical properties including tensile strength, yield strength, tensile elongation or reduction in area, and notched-bar impact resistance are affected in a similar manner. These properties do not depend upon the particular alloy elements present in the steel.

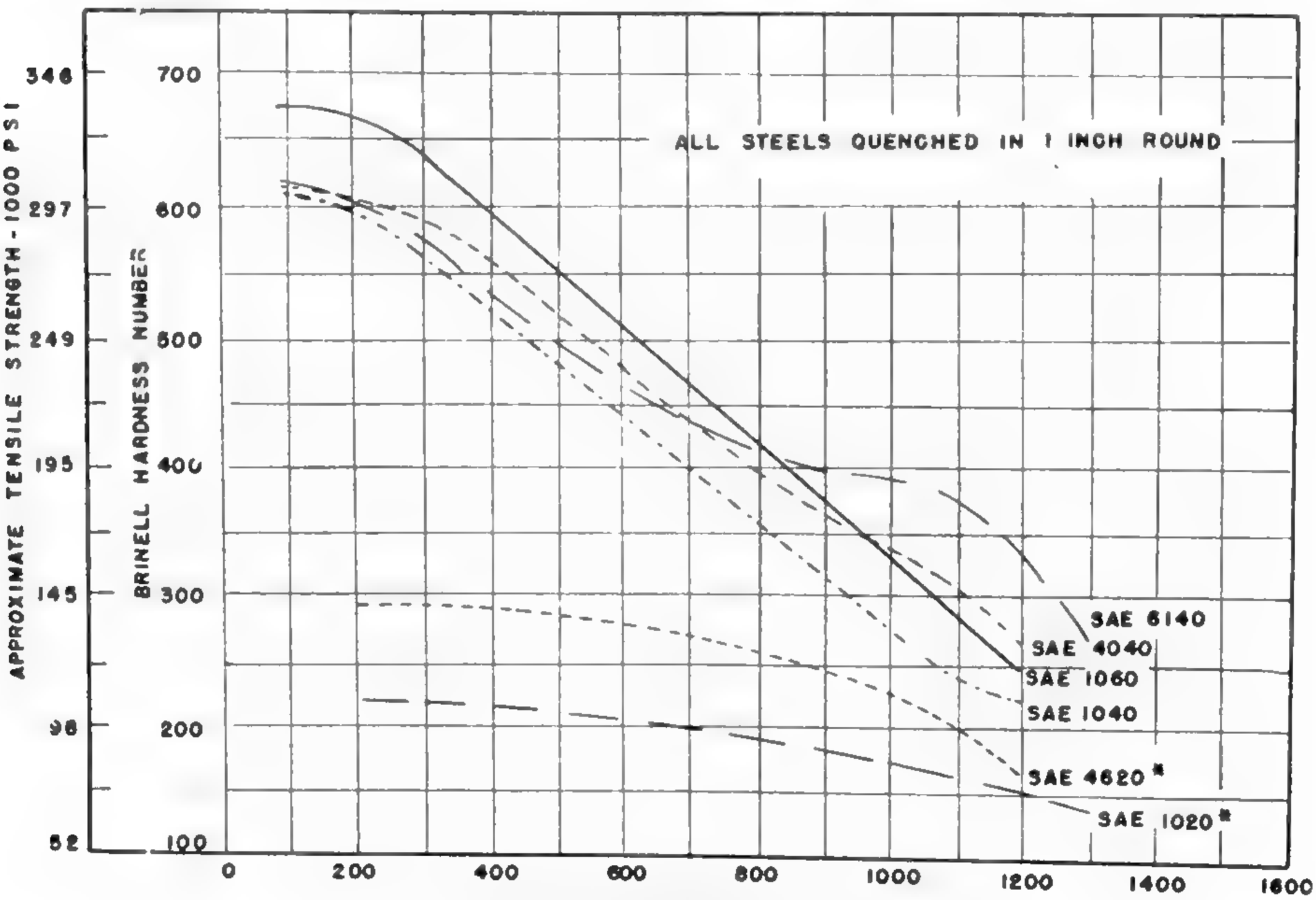

Fig. 6.—Approximate Tensile Strength of Several Quenched Steels as a Function of Tempering Temperature

Steel which has been quenched is given a second heating and cooling treatment called tempering. The tempering operation is carried out at a temperature below the critical transformation temperature and serves to distribute the carbon as uniformly dispersed carbide spheroids.

If a steel is not fully hardened to martensite before tempering, the yield strength will be low in relation to tensile strength and hardness, and the notched-bar impact resistance will be inferior. Thus, the principal benefit of alloy additions to steel is to increase the harden-

ability, i.e., the depth of hardening of moderate or large section pieces following liquid quenching.

Figure 7 gives the approximate relationships between hardness and tensile strength, yield strength and Charpy V-notch impact resistance for properly heat-treated steels. The notched-bar impact resistance is affected by the relation of the test specimen to the direction of rolling, as indicated in Fig. 7. Alloy steels, particularly those high in manganese or chromium may also develop *temper brittleness* which appears when they are tempered in the temperature range of 700 to 1100° F. or slowly cooled from tempering temperatures above 1100° F., but not if they are rapidly cooled from tempering temperatures above 1100° F. The only property measurably affected is notched-bar impact resistance. Moderate additions of molybdenum tend to decrease temper-brittleness susceptibility.

welding will be discussed in a later section of this chapter. Welding on the hardened face of carburized steel without localized cracking or softening is very difficult and is usually avoided by masking, before carburizing, the areas to be welded.

Normalizing is accomplished by heating to temperatures above the critical transformation and cooling in air. Normalized steels have mechanical properties similar to those of hot-rolled steels which are cooled at the same rate. Normalizing is sometimes practiced to promote uniformity of properties and grain size, particularly of steels for elevated- or low-temperature service, since the heating temperature for normalizing is more closely controlled than the temperature for hot-rolling. Tempering after normalizing has little effect upon the tensile strength or ductility of readily weldable steels except for those containing copper which may be

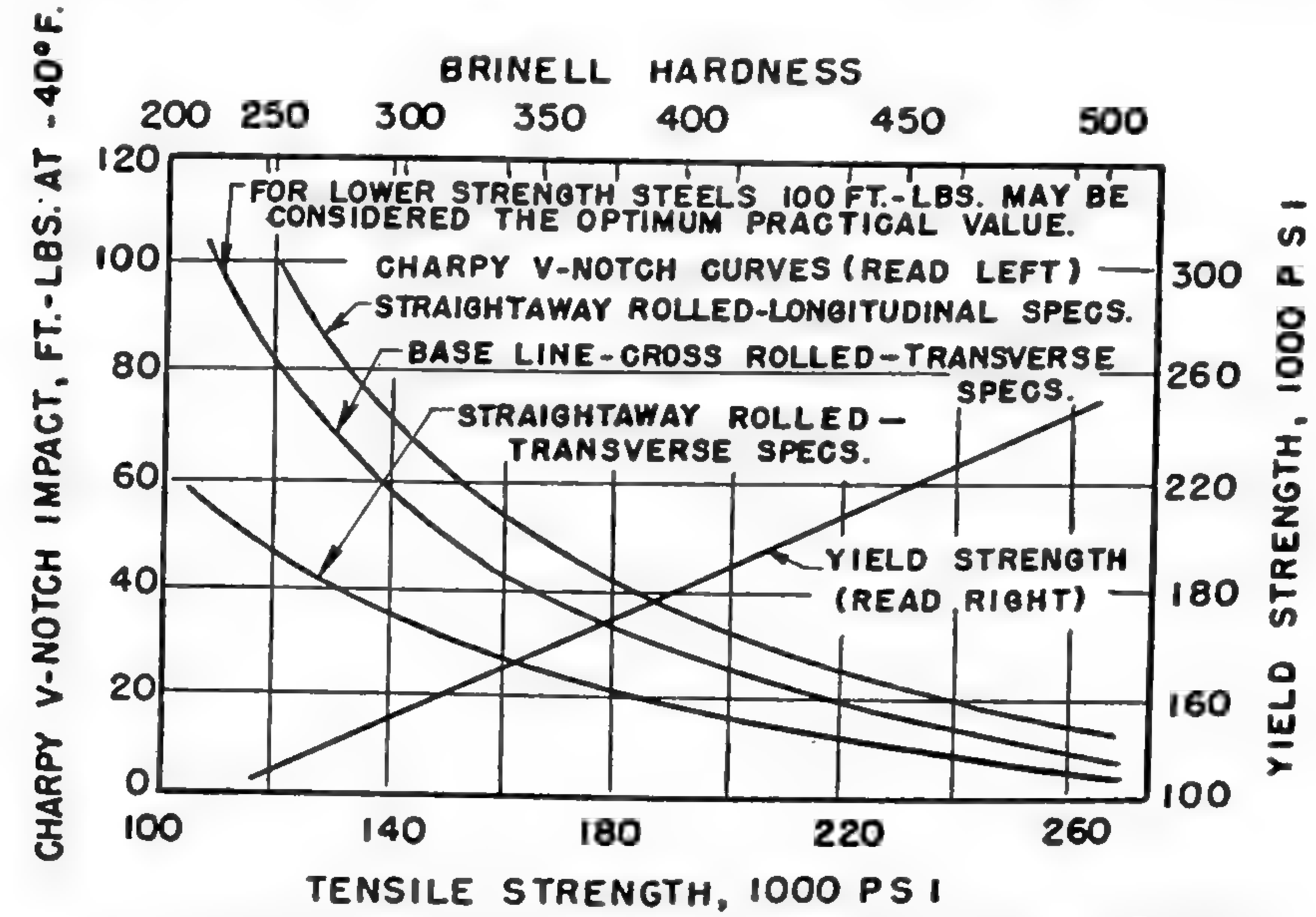

Fig. 7.—Relationship of Yield Strength, Charpy V-Notch Impact Resistance, Hardness and Tensile Strength of Properly Heat Treated and Reasonably Clean Steels

Besides quenching and tempering, other heat treatments such as normalizing, normalizing and tempering, annealing, or case hardening by carburization or nitriding are used in processing steel. The influence of those heat treatments which affect carbide stability or alloy homogeneity on cracking tendency during precipitation hardened. The yield strength at a given offset may be raised because of the relief of stress accompanying tempering.

Corrosion Resistance

None of the low-alloy steels are rustproof. An addition of about 12% of

chromium is required to make steels stainless enough to remain substantially rustproof under normal atmospheric exposure. However, the presence of small amounts of some of the alloying elements, singly or in combination, provides a marked improvement in resistance to atmospheric corrosion and certain other mild corrosive media. The initial attack on these steels is as rapid as in plain-carbon steels, but a continuous, adherent, relatively non-porous oxide film is developed and slows down the subsequent attack and selective pitting.

There is a marked increase in atmospheric corrosion resistance over plain-carbon steel as the copper content is increased to 0.20%. Further increases produce little additional improvement. Small amounts of copper alone give about a 2-to-1 decrease in atmospheric corrosion. Phosphorus similarly improves atmospheric corrosion resistance and, in combination with copper, the influence is considerably greater than with either element alone.

Table 5 shows some results of tests carried out by Greenidge and Lorig on three-year exposure of various low-alloy steels to atmospheric corrosion. These tests indicated that individual additions of silicon, nickel or molybdenum were little more effective in increasing the corrosion resistance of copper-bearing steels than is copper alone. Although 1% chromium is said to have negligible effect on corrosion resistance of low-silicon, low-alloy steels, its addition to steels high in silicon and phosphorus appeared quite effective, and the corrosion resistance was further improved by the addition of copper. The latter steel containing copper, chromium, high phosphorus and high silicon lost only about one-fourth as much weight as the base iron.

Table 5—Weight Loss of Low-Alloy Steels on Three-Year Exposure to Atmospheric Corrosion

Composition, %								Average Weight Loss Mg./Sq. Cm. of Surface
C	Mn	Si	P	Cu	Cr	Ni	Mo	
0.02	0.02	0.15	0.02	...	...	...	...	120
0.02	0.02	0 15	0.02	0.20	...	...	...	80
0.02	0.02	0 15	0.02	0.75	...	...	...	74
0.02	0.02	0 15	0.02	2.00	...	...	...	72
0.25	0.30	0.15	0.02	0.40	...	...	...	74
0.02	0.02	0.60	0.02	0.40	...	...	...	78
0.02	0.02	0.15	0.02	0.40	...	0.40	0.20	68
0.09	0.31	0.61	0.14	...	0.96	...	...	57
0.09	0.29	0.61	0.14	0.31	0.96	...	...	42

Where appearance of low-alloy steels is important, a protective coating is needed.

Low-Temperature Properties

The tensile strength of steel increases with decrease in testing temperature. Tensile ductility is not markedly affected until very low testing temperatures. At liquid air or lower temperatures, however, normalized ferritic steels lose ductility and unkilled low-carbon steels become brittle, but properly deoxidized, quenched and tempered steels retain high ductility in the static tensile test at −300° F.

Low-temperature brittleness as evidenced by the notched-bar impact test occurs as the temperature of test is decreased below room temperature, the temperature of embrittlement depending upon the composition and treatment of the steel. Table 6 shows a comparison of the influence of heat treatment for one steel.

The low-temperature notch sensitivity of hot-rolled or normalized steels may be improved by low carbon content, aluminum deoxidation and suitable selection of alloying elements. Wide differences exist in reported impact values from various normalized steels, depending upon the type of specimen and the direction of the bar with respect to the rolling direction of the steel. When impact specimens are taken parallel to the principal direction of rolling or forging, the values may be considerably higher than when the bars are taken in the transverse direction.

The best quenched and tempered steels show good impact resistance at −100° F., but generally fall off to values below 15 ft.-lb. by the time the temperature is down to that of liquid air (−300° F.). Unless heat-treated steels are fully hardened during quenching, or if they are subject to temper brittleness, loss of notched-bar impact resistance may occur at low atmospheric temperatures (0 to −40° F.). This is of particular concern when the steel is heat treated in large sections or used in sections where the restraint is greater than for the conventional Charpy bar. A great deal may be accomplished by design of structures to avoid stress concentrations.

Table 6—Mechanical Properties of Steel for Two Treatments

	Chemical Analysis, %						
	C	Mn	P	S	Si	Mo	Al-Killed, Boron-Treated
	0.26	1.68	0.013	0.021	0.24	0.33	
	½-In.-Thick, Cross-Rolled Plate						
	Heat Treatment						
	1600° F. Water Quench 1200° F. Air Cooled						1600° F. Air Cooled 1140° F. Air Cooled
Tensile strength, psi. at							
+70° F.	130,600–131,600						122,000–122,800
—110° F.	153,200–157,000						138,000–138,000
—319° F.	188,200–188,200						110,000–160,000[a]
Reduction of area, % at							
+70° F.	62.0–63.0						58.5–58.5
—110° F.	56.7–58.1						54.1–54.1
—319° F.	47.4–47.0						.....
Elongation, % at							
+70° F.	20.7–20.7						20.0–19.3
—110° F.	21.4–20.7						19.3–20.7
—319° F.	22.9–20.7						.....
Charpy V-notch impact,[b] ft.-lb. at							
+212° F.	50–54						21–14
70° F.	55–55						8–6
0° F.	....						3–4
—40° F.	55–55						3–3
—100° F.	51–45						....
Bend load,[c] lb. at							
+70° F.	31,500						23,000
—40° F.	32,000						21,000

[a] Broke in threads at grip.
[b] Bars transverse to principal direction of rolling; notched perpendicular to plate surface.
[c] Bars ½ in. wide, 1½ in. deep, with V-notch 0.08 in. deep and 0.002 in.-radius, 6 in.-breaking span; single load center of span, notch on tension side.

For extreme service conditions, high-alloy austenitic steels which show only mild decrease in notched-bar impact resistance at low temperatures are to be preferred. Recently, steels of about 9 percent nickel have been developed. When suitably treated, these steels have a partially austenitic structure and maintain a notched-bar impact resistance above 15 ft.-lb. at a testing temperature of —320° F. A recommended composition is 0.12 C max., 0.35 to 0.80 Mn, 0.15 to 0.30 Si, 0.04 S max., 0.04 P max., 8.25 to 9.25 Ni. Heat treatment, including double normalizing and reheating to 1050° F. subsequent to forming or welding is recommended. The notch toughness of these steels drops rapidly with an increase in carbon content; it is almost halved by going from 0.09 to 0.18% carbon.

Elevated-Temperature Properties

The low-alloy steels commercially available that are used for high-temperature applications range from plain carbon-molybdenum steel, through a series of low chromium-molybdenum steels, and up to an alloy steel containing 9% chromium and 1% molybdenum.

Table 7 shows the nominal compositions of the alloy steels available. To this list have been added two steels for which data have recently become available; namely, the 0.50% Cr, 0.50% Mo steel and the 1% Mo, 0.2% V steels. For purposes of comparison, plain-carbon steel is included in both this table and in Table 8 which gives creep data.

These are the steels which are widely used in the steam power industry and in the petroleum refining industry. The choice among these steels varies with the requirements of load-carrying ability and the corrosion and oxidation conditions for the service application under consideration.

Plain-carbon steel is by far the largest tonnage steel used at elevated temperatures, but its use is restricted to service applications where corrosion and oxidation resistance are not important and where the temperature does not exceed 1000° F.

Carbon-molybdenum steel (0.50% molybdenum) is suitable for higher stresses than carbon steel but provides little increase in resistance to corrosion or oxidation. This steel has been widely used for power piping in the range 900 to 975° F. and in petroleum cracking tube furnaces at 1000 to 1100° F. when corrosion and oxidation conditions are not serious.

As a result of the reported graphitization of carbon and carbon-molybdenum steels, two new steels have been recently

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proposed. One contains about 0.5% chromium, 0.5% molybdenum and the other about 1% molybdenum, 0.2% vanadium. Both of these steels appear to have very good creep and rupture properties at 900 and 1000° F. and are reported to be adequately resistant to graphitization at 1000° F.

The balance of the steels indicated in Table 7 contain chromium and molybdenum, some with additions of aluminum and silicon. Chromium, silicon and aluminum are the additions made to procure surface stability with regard to oxidation and corrosion resistance, and the latter two elements are more effective when chromium is present. Several nickel-chromium-molybdenum cast steels are used for high-temperature service. Slightly improved surface stability is reported for these nickel-containing steels.

Steels with 2, 3, 5, 7 and 9% chromium are available; some with aluminum and silicon (over 1%) additions. As temperatures approach 1200° F. and continue on up to 1500° F., higher chromium contents are required for oxidation resistance and in particular to give adequate corrosion resistance to hot petroleum products.

The carbide-forming elements which have been found most effective in improving high-temperature strength characteristics are chromium, molybdenum, tungsten and vanadium, but for economic reasons tungsten and vanadium are seldom used. High-temperature strength does not necessarily increase continuously with increasing additions of any of these elements; in most instances the maximum creep resistance corresponds to certain critical amounts. This is illustrated in Fig. 8 which shows the influence of chromium and molybdenum content on a series of steels containing 1.0% silicon.

At 1100 and 1200° F. the maximum creep strengths are obtained with chromium of about 5.0 and 3.0%, respectively, and the creep strengths then decrease as the chromium content is increased to 7 and 9%. In general, the strength is further improved by raising the molybdenum content from 0.5 to 1.0%, with additional gains the greater the chromium content.

The fact that creep strength decreases as the chromium exceeds a certain amount should not imply that these higher alloy steels are unsatisfactory for high-temperature service. Under conditions of severe oxidation or corrosion such as in some oil refinery applications, these higher chromium steels will actually have a better load-carrying ability than the lower alloyed ones due to their greater surface stability.

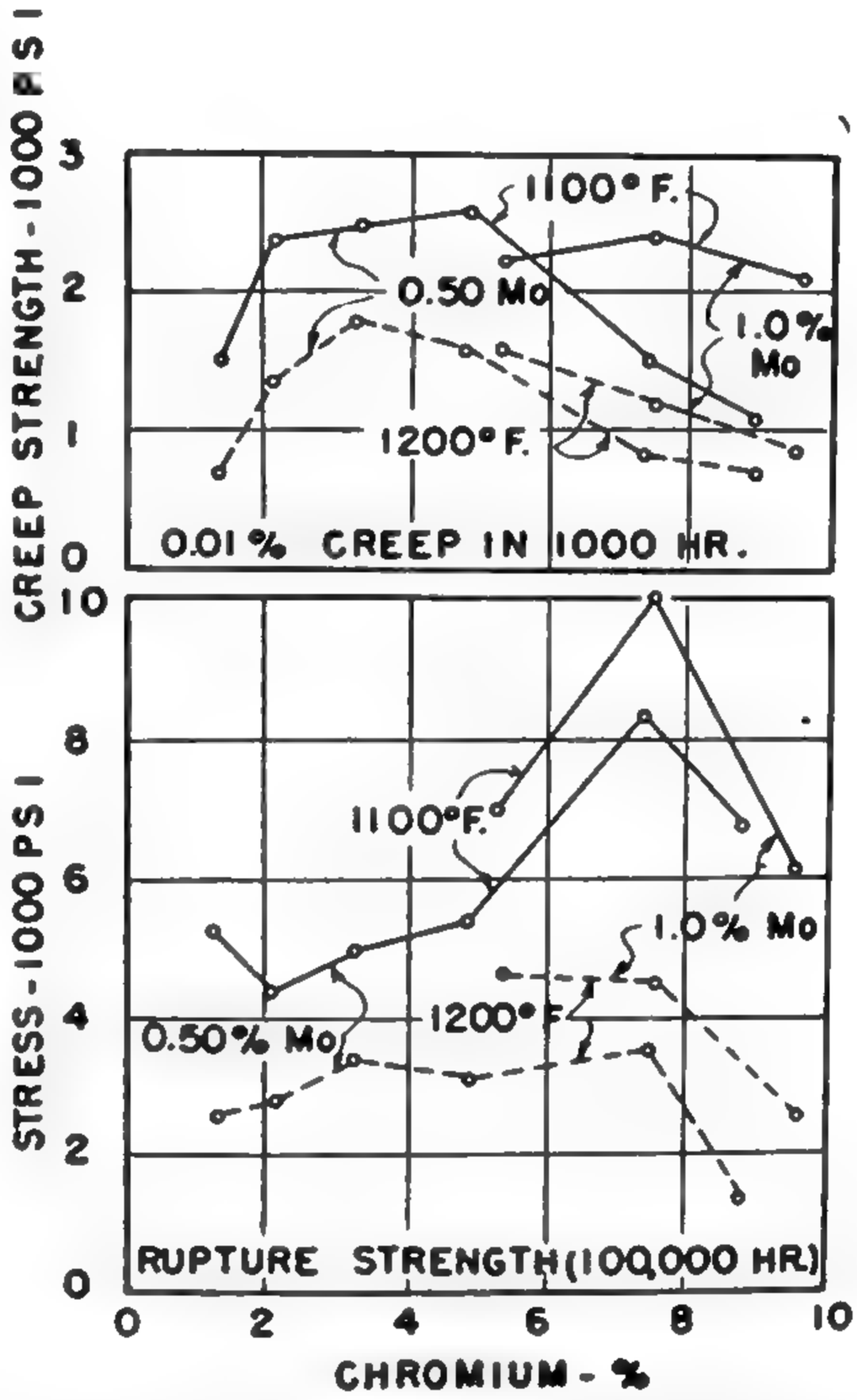

Fig. 8.—Influence of Chromium and Molybdenum Content on Creep Strength and Stress-Rupture of Steels Containing 1% Silicon

Evaluation of the load-carrying ability of the intermediate alloy steels is complicated by the fact that the laboratory results rate the steels differently depending on the rate of deformation used. This is illustrated in Fig. 8 which shows that for the 100,000-hr. rupture strength, the higher chromium alloys are superior; whereas, for creep strength the lower chromium alloys appear best.

Many of these alloy steels, like most plain-carbon steels, have a wide range of high-temperature strengths depending on the steelmaking practice (deoxidation practice), the conditions of fabrication, heat treatment, the duration of the expected service life and the extent of the permissible deformation.

Strengths may be considerably different depending upon whether the steel is aluminum- or silicon-killed. Large alumi-

num additions producing fine-grained steels have been generally proved to lower creep strength and to contribute to susceptibility to graphitization of plain carbon-molybdenum steels. The addition of 0.5% or more of chromium has been indicated definitely beneficial in inhibiting graphitization, but it is possibly too early to indicate whether 0.5% chromium is sufficient for all applications. The fabrication process and the subsequent heat treatment used, if any, have a marked effect on high-temperature strength.

It is strongly recommended that, for any particular applications, the producers of these types of low-alloy steels be consulted for recommendations as to the steel best fitted to the requirement. Allowable stresses at various service temperatures for many of these steels are given in the ASME Boiler Construction Code.

HOW TO WELD

Metallurgical Response to Welding

The metallurgical behavior of low-carbon alloy steels, when subjected to the thermal cycle developed during welding, does not differ widely from that of plain-carbon steel. The addition of small amounts of the alloys commonly used affects the metallurgical response principally because of the influence upon the austenite transformation during cooling. The alloys produce a lag in the transformation causing the hard martensitic structure to be formed under less drastic cooling conditions and promote the retention of austenite which may transform at or near room temperature with possible detrimental effects as will be discussed later. Alloy content does not affect the maximum hardness that can be developed in the heat-affected zone as the hardness is a function of the carbon content. The addition of most alloys, however, causes a lag in the transformation during cooling so that the maximum hardness may be developed with a slower cooling rate or less drastic quench than would otherwise be required. As a result, therefore, preheating and postheating treatments, for reducing the cooling rate in the heat-affected zone, that are entirely adequate for producing the desired metallurgical structure in the heat-affected zone in plain-carbon steel may be inadequate for alloy steels because of this lag in austenite transformation. It is generally desirable to have the cooling rate sufficiently slow to form the relatively tough bainite structures instead of the hard martensite.

Cold-Cracks.—The most obvious difference in the behaviour of alloy and plain-carbon steels is the susceptibility of the alloy steels to cold cracking in the heat-affected zone when subjected to metal-arc welding, unless special precautions are taken. Illustrations of typical cold cracks, both toe and underbead cracks, are shown in Fig. 9.

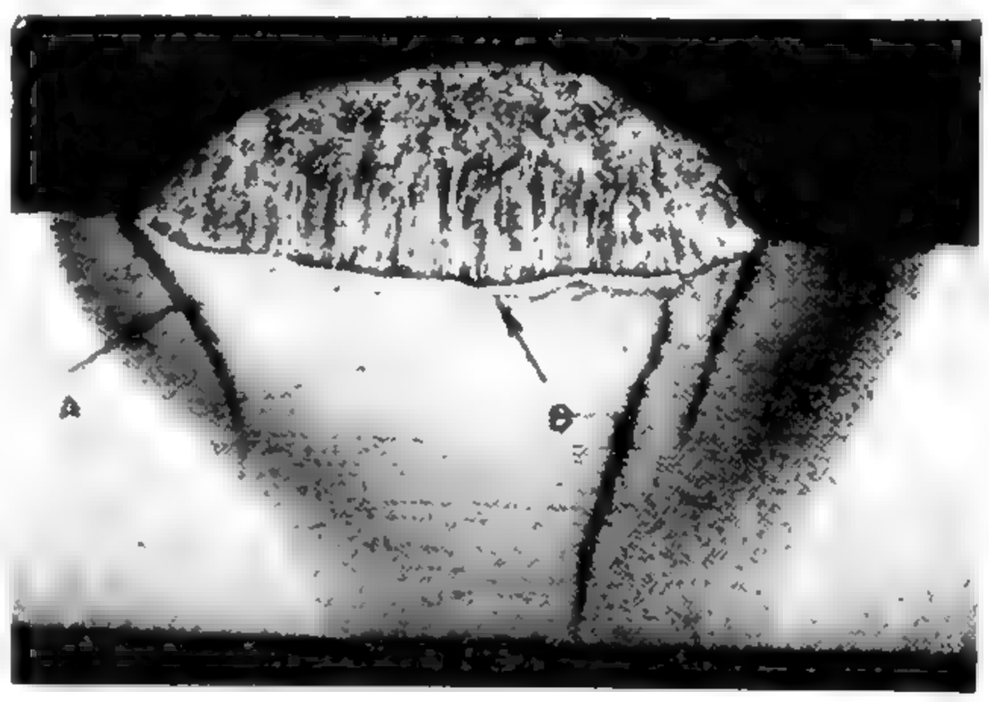

Fig. 9.—Cross Section of Weld Bead on ⅛-In. SAE 4130 Steel Plate Showing Toe Cracks (*A*) and Underbead Cracks (*B*). (Magnification 12×)

In order for underbead cracks to develop in the heat-affected zone, at least two conditions are believed to be necessary: First, the steel must have sufficient hardenability and the cooling rate must be rapid enough so that a hard martensitic area is formed; and second, an appreciable amount of hydrogen must be taken up from the atmosphere during welding. Other factors, such as retained austenite which transforms at or near room temperature and stress developed in various manners, are suggested to explain the mechanism by which these cracks originate.

There is now sufficient information available to show that restraint and thermal stresses in the weld are not the primary causes of underbead cracking but are responsible only for crack propagation. The evidence indicates that the hard martensite structure is embrittled or ruptured in some manner by the hydrogen and that the cracks are then propagated by restraint and thermal stresses.

In order to prevent underbead cracking in the low-alloy steels, care must be exercised in the selection of the factors con-

trolling the cooling rate of the heat-affected zone. The optimum conditions are those which, during the cooling cycle, promote complete transformation of the austenite at a relatively high temperature. If the transformation is completed at a sufficiently high temperature, which can be accomplished by slow cooling, the presence of hydrogen is not detrimental. The high-temperature transformation prevents the formation of the hard martensitic structure and the slower cooling rate provides more time at elevated temperature for the hydrogen to diffuse out of the steel. The possibility of retained austenite is also reduced. Since the addition of the alloys commonly used causes the steel to transform more sluggishly, it is obvious that slower cooling rates are required than for plain-carbon steels.

While the optimum theoretical cooling rate may be approximated from S-curve data, this is not a satisfactory approach to the practical problems of arc welding because of the extreme difficulty in determining the cooling rate in the heat-affected zone and because of the influence of banding or alloy segregation which will be discussed later. In practice, therefore, the preheating and postheating cycles used for controlling the cooling rate are usually established empirically from past experience and experimentation.

More success has been had in applying cooling-curve data to spot welding where heating and cooling conditions can be more easily measured and controlled and hydrogen is not a factor.

In addition to the cooling rate and the chemical composition of the steel, the rate of heating may be important since wide ranges may be encountered, depending upon the welding process used, such as the extremely rapid rates developed in spot welding and the slow heating developed in oxy-acetylene welding. Another variable which is especially important in metal-arc welding is the atmosphere surrounding the arc since this may be a source of hydrogen.

Recently, special electrode coatings have been developed that are low in hydrogen-producing ingredients, thus reducing the hydrogen content of the arc atmosphere (see Chapter 38). Together with preheat and postheat, such factors as the section size, power input, rate of welding and number of passes all affect the rate of heating and cooling.

Influence of Different Alloys.—The alloying elements commonly used in low-alloy steels, in addition to carbon, are chromium, copper, manganese, molybdenum, nickel, phosphorus, silicon and vanadium. The effect of these elements upon the metallurgical response during welding is similar to their influence upon hardenability. The steels with high hardenability are those which transform sluggishly and, therefore, can be fully hardened with a relatively slow cooling rate.

In addition to carbon, which has the most pronounced effect, manganese, molybdenum and chromium (Fig. 10) increase the hardenability to a marked extent, while copper, nickel and silicon are much less effective.

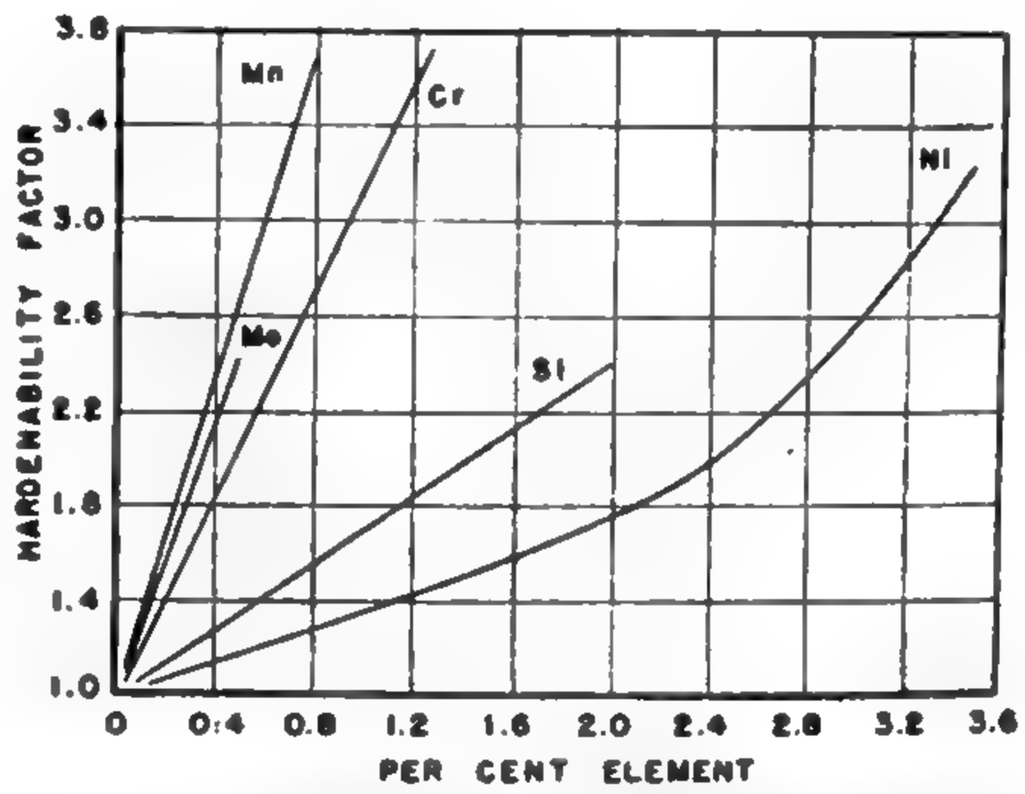

Fig. 10.—The Effect of Various Elements Upon the Hardenability of Steel

While the influence of vanadium, especially when present in amounts of 0.03% or less, is a controversial subject, it appears that the hardening effect of this alloy is relatively insignificant. Phosphorus, although usually present in a small amount, increases the hardenability and should be considered when used as an alloy.

Since the carbon content establishes the maximum hardness that may be developed upon rapid cooling, and because of its influence upon hardenability, the carbon content is usually kept low in alloy steels that are to be fabricated by welding.

It is generally considered advantageous to obtain the desired tensile properties by the addition of small quantities of several alloys instead of using a larger addition of a single element, because experience has indicated that the combination is more effective and that less difficulty is experienced with weld cracking and more de-

sirable properties may be developed in the heat-affected zone.

Influence of Microstructure.—It has been recently recognized that the microstructure may also play an influential part in determining the behavior of a steel in the heat-affected zone adjacent to the weld. This effect is especially noticeable in alloy steels when the thermal cycle during welding is extremely rapid. If the prior thermal history of the steel has been conducive to the development of stable carbides, such as chromium, molybdenum or titanium carbides of relatively large size, the steel will respond to a rapid heating and cooling cycle in a manner similar to that of a lower carbon steel The reason for this is that during the short heating period, there is not sufficient time for the carbides to dissolve completely and diffuse throughout the austenite. A portion of the carbon is, therefore, retained as carbides, thus effectively reducing the carbon content of the austenite which controls the behavior during subsequent cooling. In the finer, less stable carbide structures, practically all of the carbon may be effective because of the greater ease with which the carbides can go into solution upon heating.

Since the response to thermal processing during manufacturing may be influenced by the deoxidation practice used in making the steel, the aluminum content and other special deoxidizers that may be present may indirectly influence the metallurgical response during welding because of their previous effect upon the structure. This phenomenon is illustrated in Fig. 11 which shows how differently SAE 4130 steel, processed in a manner similar to aircraft tubing, responds to a rapid thermal cycle depending upon the deoxidation practice used in the steel manufacture. These dilatometer cooling curves indicate a marked difference in the behavior of the carbides, with those in the aluminum-titanium-treated steel being the least soluble.

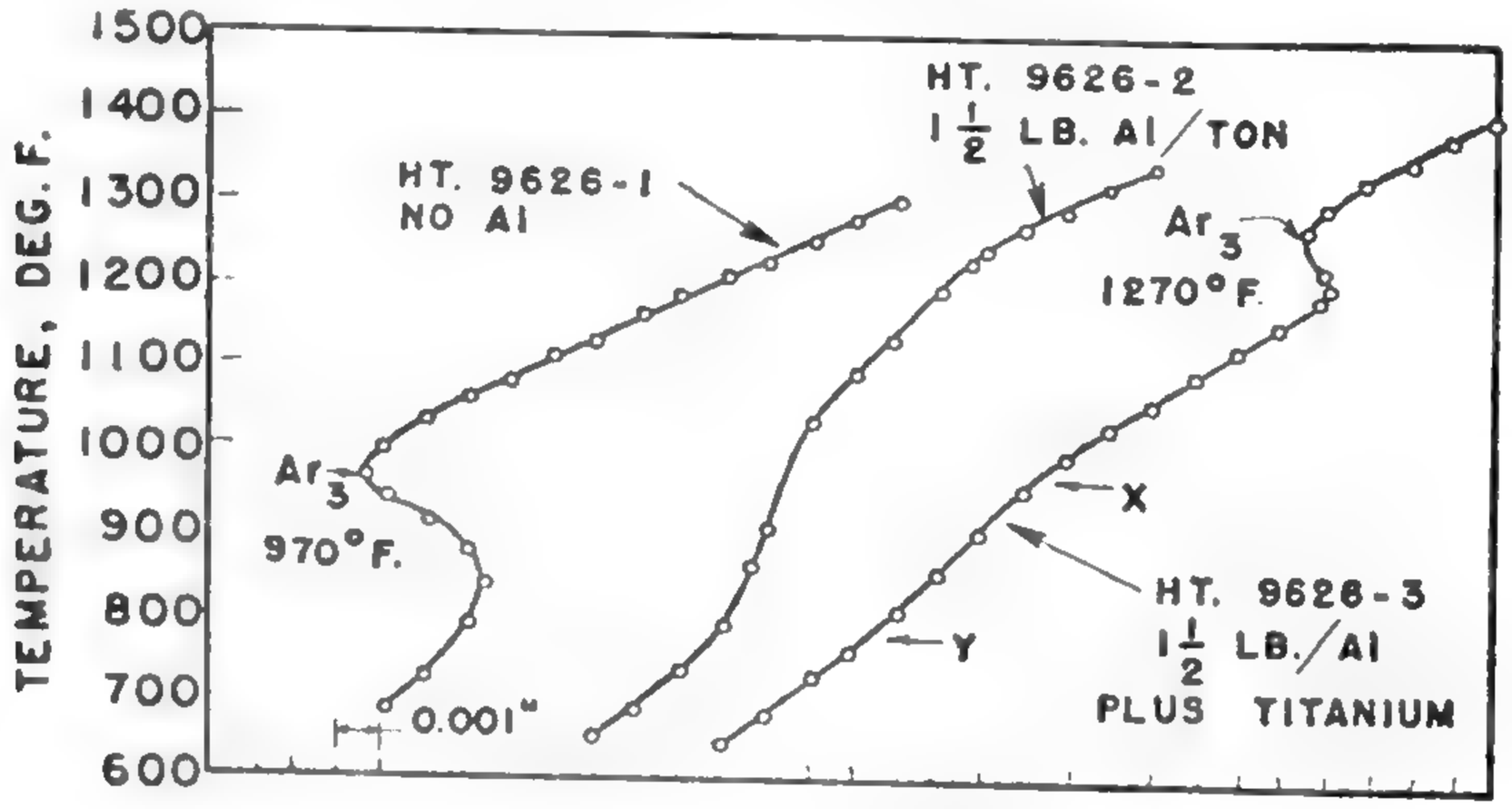

Fig. 11.—Dilatometer Cooling Curves Following Rapid Heating Showing the Effect of Aluminum and Titanium Additions to SAE 4130 Steel

When the welded structure is subjected to shock or low-temperature service, the microstructure of both the base metal and heat-affected zone are important. It is generally recognized that notch toughness and resistance to crack propagation are inferior in the following microstructures: (a) a large amount of ferrite; (b) upper bainite; and (c) an excessive amount of untempered martensite. Better performance is associated with lower bainite or tempered martensite microstructures.

Alloy Banding.—Alloy banding has been found to have a pronounced effect upon underbead cracking associated with metal-arc welding, the cracking being more severe in the strongly banded steels. The data in Fig. 12 show how the underbead cracking was reduced in a high-strength structural steel by homogenizing at 2350° F. for 4 hr. in order to minimize the manganese banding.

Banding originates with the dendritic structure of the ingot and persists through the subsequent processing. The presence of alloy banding frequently can-

not be determined from the microstructure of the hot-rolled or normalized steel, but can be readily detected after slow cooling from above the critical temperature. If the cooling is sufficiently slow during the austenite transformation, the carbon diffuses into the remaining austenitic areas, the last of which are the high-alloy bands. When the bands finally transform, their locations are outlined by bands of pearlite as a result of the carbon concentration.

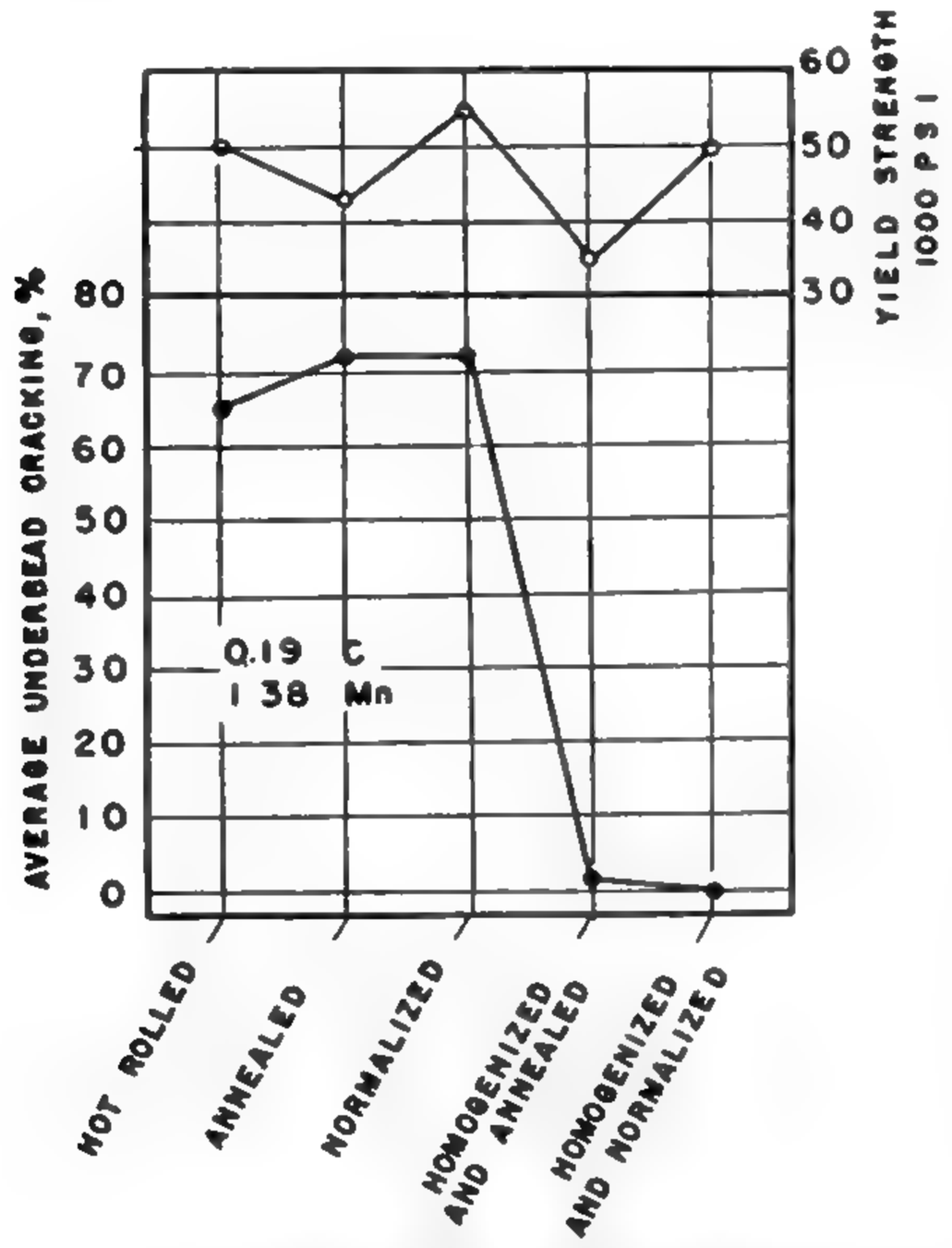

Fig. 12.—Effect of Homogenizing Treatment on the Underbead Weld-Crack Sensitivity of a High Strength Structural Steel

The alloys in the bands diffuse very slowly even at relatively high temperatures and obviously persist in the austenite following the heating cycle during welding. The metallurgical response of such a structure is, therefore, similar to that of a composite steel consisting of small sections of high- and low-alloy steels instead of a homogeneous material. For this reason, it is difficult to determine the desired cooling rate from S-curve data since the chemical analyses of the banded areas are unknown, and banding may be expected to a greater or lesser degree in all commercial steels.

General Procedures for Various Welding Processes

Basic Factors.—The general procedures which are recommended for the various welding processes should be evaluated by the following factors:

1. Welding Design.
2. Joint Geometry and Preparation for Welding.
3. Joint Welding Procedure.
4. Heat Treatment Subsequent to Welding.

Design.—This factor is of considerable importance in the higher strength alloys where mechanical properties in the heat-treated conditions exceeding 100,000 psi. tensile strengths are required. For the low-alloy steels which are used in the hot-rolled condition, and in which the tensile strengths do not exceed 100,000 psi., this factor is not so important. For these grades of steel the same consideration which is given to mild steel welding is generally applied. For the heat-treated grades of low-alloy steels consideration of design should be given and the welds located, whenever possible, at the least critical sections. Consideration must be given to the location of welds in order that they may be accessible for thorough inspection. Where high tensile welds are used and where failure of such welds may result in loss of life or great property damage, accessibility of the welds for adequate inspection is of extreme importance. For these critical welds, it is necessary that both sides of the completed weld be accessible for the various methods of inspection. Non-destructive inspection methods, such as radiography and magnetic particle inspection, are most commonly used. Other non-destructive methods, such as the use of flaw detection oils and supersonic testing are also employed. On some highly stressed structures, proof testing is required, which may or may not be substituted for some of the other inspection methods. In all cases where high tensile strengths are required, it is important that the welding procedure and the operators be properly qualified.

Joint Geometry and Preparation for Welding.—Design of welding grooves for the hot-rolled grades of low-alloy steels is the same as used for mild steel. For the heat-treated grades of alloy steel, special attention to the design of the welding grooves must be given. The design of the joint should be such that full penetration of the weld metal can be readily obtained. V-grooves with root openings and with backings are commonly

employed. In some cases the parts are machined in such a manner that an integral backing is used. The grooves are machined or oxygen cut to certain dimensions, and usually the parts are accurately machined so that groove dimensions are as uniform as possible. Figure 13 shows an airplane landing gear made from heat-treated low-alloy steel, which is of welded construction and in which welding grooves were accurately machined to close tolerances so that uniform quality was obtained.

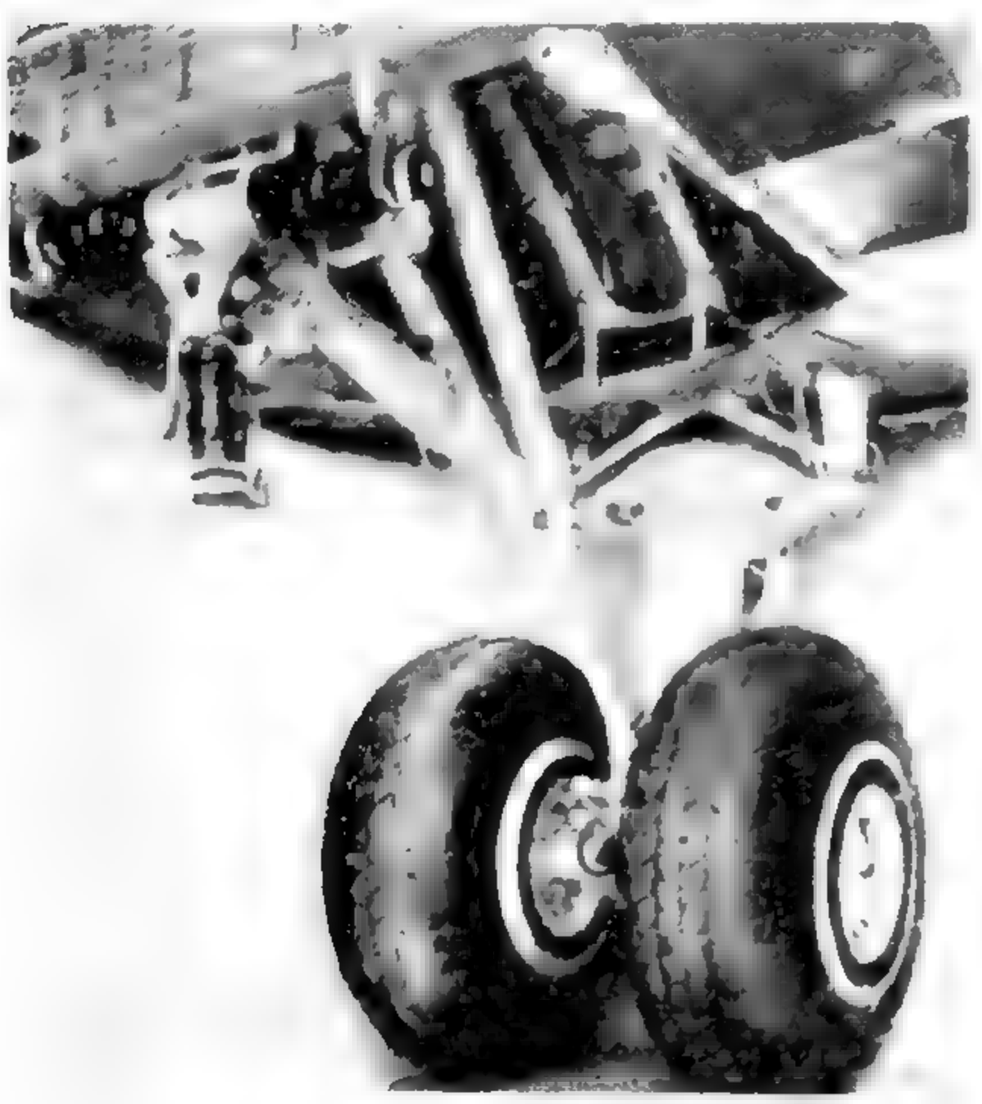

Fig. 13.—Welded Airplane Landing Gear

The design of grooves will also depend to some extent upon the thickness of the material and its location and upon the different welding processes which are used.

Joint Welding Procedure.—The welding procedures, with respect to preheat, postheat and the welding conditions used, depend to a large extent on the composition of the materials being welded and also on the welding process used. The *AWS Standard Qualification Procedure* or the *ASME Boiler Construction Code*, Section IX, might be referred to as a guide in qualification of welding procedures.

Heat Treatment Subsequent to Welding.—The heat treatment given to the hot-rolled grades of low-alloy weldments may consist either of a stress-relief heat treatment for the relieving of high residual stresses or for reasons of machining stability. For some grades of alloys, stress relief is performed at 1150 to 1200° F. For the precipitation-hardening types of alloy steels, stress relieving is usually carried out at lower temperatures where it also increases the tensile strength of the weld metal. In any case, the stress-relief heat treatments for the various types of hot-rolled alloy steels must be given careful consideration. For many applications, the stress-relief heat treatment is not necessary and is not required. Post-heat treatment for the heat-treated grades of low-alloy steels is usually mandatory and may consist either of a stress-relief heat treatment or a complete heat treatment to develop required mechanical properties. For high-strength weldments, where the tensile strength requirements are in excess of 100,000 psi., complete heat treatment after welding is generally recommended. This heat treatment usually obliterates the heat-affected areas adjacent to welds and also reduces localized welding stresses. When stress-relief heat treatment is used, the stress-relieving temperatures may range from 700 to 1200° F. depending upon prior heat treatment of the parts.

Metal-Arc Welding

Shielded Metal-Arc Welding.—The shielded metal-arc welding process is commonly used in the welding of hot-rolled, low-alloy steels. Electrodes which are available for welding these steels have been classified by the AMERICAN WELDING SOCIETY and are commercially available for a wide range of tensile properties (see Chapter 38). Several basic types of electrodes are available for the welding of alloy steels, such as the shallow penetration, deep penetration and low-hydrogen, commonly referred to as the lime-ferritic types of electrodes. The shallow penetration type of electrode is often preferred on the low-alloy, hot-rolled grades of steels because it causes little dilution of the base metal to occur. This type of electrode is most commonly used for making fillet welds in this class of alloy steels. For making butt welds, or where deeper penetration of the weld metal is required, the low-hydrogen type of electrode is very satisfactory. These types of electrodes are available in various ranges of tensile strength. For many applications, where single layer deposits give sufficient strength, mild-steel elec-

trodes of the E60 series are used. Where greater strength of the weld metal is required, the higher tensile electrodes are used.

For the heat-treated grades of low-alloy steel, in which tensile strength in excess of 100,000 psi. is required after heat treatment, electrodes of the E 100 Series are generally used.

Austenitic types of electrode are also commonly used in the welding of the hot-rolled and heat-treated alloy steels. These electrodes are usually used after the base plates have been heat treated. In general, it is recommended that the post-welding treatment should not exceed a stress-relief heat-treatment temperature of 1150 to 1200° F. The following standard classifications of austenitic electrodes are used—E 310 (25 Cr–20 Ni), E 309 (25 Cr–12 Ni) and E 308 (19 Cr–9 Ni).

Figure 14 shows a shielded metal-arc welded aerial torpedo made from heat-treated low-alloy steel. The welds have a tensile strength in excess of 120,000 psi. This air flask contains a number of girth seams which were manually welded using coated high-tensile electrodes. (See Chapter 10 for further information on the fundamentals of shielded metal-arc welding.)

Inert-Gas Metal-Arc Welding.—The inert-gas metal-arc welding process is being used in the welding of hot-rolled and heat-treated grades of low-alloy steels. At the present time, this process is restricted to the lighter gages of material but has applications to the welding of heavier sections. For very light sections no filler metal is necessary. Where filler metal is added, consideration must be given to the composition of such filler metal to develop the proper physical properties of the weld.

The design of welding grooves for inert-gas metal-arc welding depends on the thickness of material, in some cases being similar to that employed for shielded metal-arc welding, while for other cases it is similar to that used for oxy-acetylene welding. Procedure qualification test plates should be made to qualify the process. (See Chapter 12 for further information on the fundamentals of inert-gas metal-arc welding.)

Atomic Hydrogen Welding.—This process is used for welding hot-rolled and heat-treated low-alloy tensile steels. This process is generally restricted to use on lighter gage materials. Comments in regard to this process are the same as those applied to inert-gas metal-arc welding. (See Chapter 11 for further information on the fundamentals of atomic hydrogen welding.)

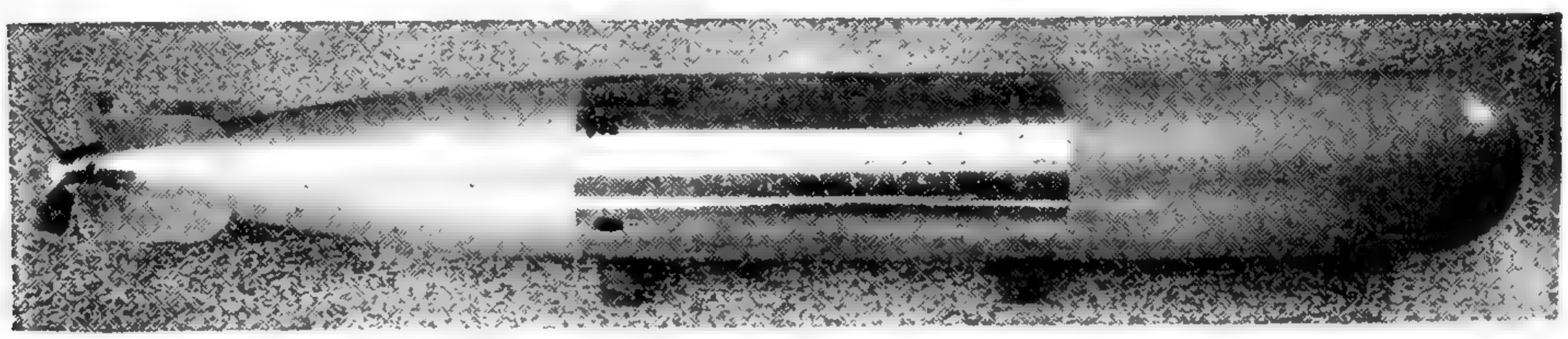

Fig. 14.—Shielded Metal-Arc Welded Aerial Torpedo

Submerged Arc Welding.—The submerged arc welding process is being used in the welding of both the hot-rolled and heat-treated grades of low-alloy steels and the method is very similar to that employed in the welding of mild steel. Special consideration must be given to the type of filler metal used to provide for adequate physical strength of the weld metal. This process can be used for light gages as well as heavier gages in which the welding can be done either in one pass or multiple-pass procedure. Various types of submerged arc fluxes are available and the proper type must be used with the alloy filler metal to obtain optimum results. Either a.c. or d.c. can be employed. Procedure qualification test plates should be made to qualify the process and to ascertain that satisfactory physical properties of the weld metal are obtained. (See Chapter 13 for further information on the fundamentals of submerged arc welding.)

Resistance Welding

Spot Welding.—A considerable amount of spot welding was used on low-alloy steels during the last war with very suc-

cessful results. For the hot-rolled grades of low-alloy steels, the welding procedure is quite similar to that used for mild steel with the exception that slight modifications are made for the increased electrical resistance of the material. The welding conditions will depend to some extent on the alloy used and on its susceptibility to hardening of the weld metal and heat-affected zone. For those alloys having high hardenability, special welding procedures were developed and were incorporated in the automatic control of the spot welding machine. It was possible to incorporate in the control preheating, welding, grain refinement and tempering heat treatments. Off-current periods for cooling between the various operations referred to are incorporated, and all of these cycles are adjustable so that the proper degree of heating and cooling can be closely controlled. Qualification of the welding cycle used is important and is usually checked by making preliminary test samples and checking these by making hardness surveys of the spot welds and also a metallurgical examination for the microstructure of the weld and base metal. (See Chapter 16 for further information on the fundamentals of spot welding.)

Seam and Projection Welding.—Seam welding is usually limited to the hot-rolled grades of low-alloy steels and to those alloys having low hardenability. The conditions for projection welding of the low-alloy steels are very similar to those used for welding of mild steel, except that in many cases a postwelding heat treatment is used to reduce the hardness of the welds. The same factors are considered for projection welding as were discussed for spot welding. (See Chapter 16 for further information on the fundamentals of seam and projection welding.)

Flash Welding.—The procedure used for flash welding of the hot-rolled grades and the heat-treated grades of low-alloy steels is very similar to that used for plain carbon steels. In some cases, the adjustment of the current and the length of burn-off varies to compensate for the higher electrical resistance of the material. Welding procedures should be established for the particular alloy which is used, and should be qualified by suitable tests to determine that the required mechancial properties have been obtained. For the heat-treated, low-alloy steels, or alloy steels which are air hardened, preheat is sometimes recommended to avoid cracking and to facilitate better welding conditions in the flash welding process. For the low-alloy steels, the welding current is usually less and the burn-off time more than for mild steels to compensate for the higher electrical resistance of the metal

Figure 15 shows a flash-welded propeller blade fabricated from SAE 4335 alloy steel. This blade was heat treated after welding. (See Chapter 17 for further information on the fundamentals of flash welding.)

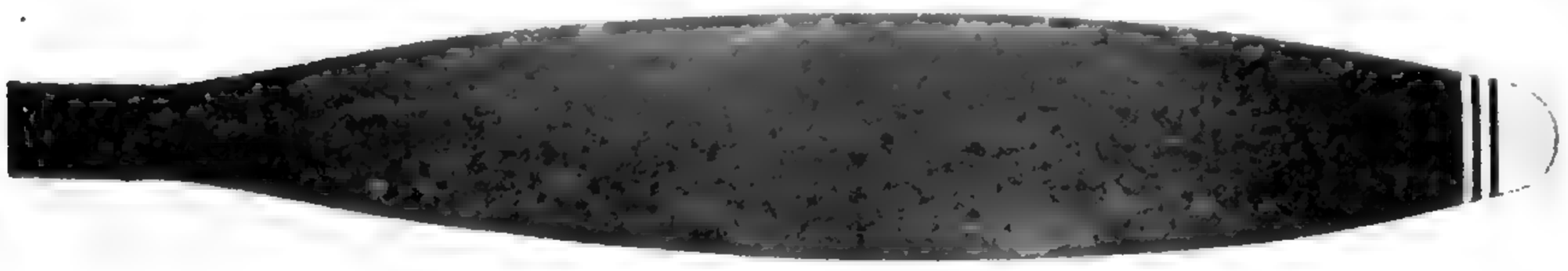

Fig. 15.—Flash Welded Propeller Blade

Gas Welding

The gas welding process is readily adaptable to the welding of the hot-rolled grades and heat-treated grades of low-alloy steels and presents no problem other

than the proper selection of filler metal which is to be added to obtain the desired physical properties. The same joint geometry construction is used in welding the low-alloy steels as is used for welding mild carbon steels. The selection of suitable filler metal is important and procedure qualification tests must be made. In some applications, filler metal different in composition than the base metal is incorporated to compensate for some of the losses which sometime occur during welding . Because the heat liberated to the adjoining plate by this process is greater than with arc welding, postheat treatment is necessary for the heat-treatable low-alloy steels to refine the grain structure. (See Chapter 5 for more detailed information on gas welding.)

Brazing

The hot-rolled grades of low-alloy steels are brazed in the same manner that is used for brazing mild steels. Special filler metal compositions are available, giving a range of shear strength for the brazed joints. The brazing operation is not recommended for the heat-treated grades of low-alloy steels where tensile strength in excess of 100,000 psi. is required or where heat treatment above 1200° F. is necessary. (See Chapter 22.)

Other Welding Processes

Pressure gas welding and thermit welding are used to weld alloy steels to a limited extent. (See Chapters 7 and 19 for information on these processes.)

COMMON APPLICATIONS

Hot-rolled, low-alloy steels, commonly called high-strength, low-alloy steels or mild alloy steels, find wide application in those fields where a reduction in thickness and weight may mean a saving in original cost or in operating costs. These steels provide an increase in the static strength, the endurance limit and the life under atmospheric corrosion as compared with plain-carbon structural steels without any material difference in weldability or ability to be cold formed.

These steels are used by all of the principal steel-consuming industries. Approximately one-half of the production of high-strength steels has been shipped to manufacturers of transportation equipment. Mining, construction, earth moving, material handling and machinery industries are important consumers. Typical applications are railroad and industrial cars (see Chapter 53), truck bodies (see Chapter 54), frames and structural members (see Chapter 47), cranes, shovels, booms, chutes, conveyors and automotive bumper face bars.

Heat-treatable steels of low carbon content and alloy content similar to or somewhat lower than that of the low-alloy, high-strength, hot-rolled grades, when properly quenched and tempered, have strength and toughness properties markedly superior to those for the hot-rolled condition. Weldability is practically equivalent for the same chemical composition.

Experience with ordnance vehicles and bombs has proved the feasibility of using steels welded in the quenched and tempered condition for highly stressed structures. Heat-treated, low-alloy steels with carbon content exceeding 0.15% are satisfactorily welded with austenitic electrodes or special types of ferritic electrodes. Welded armored vehicles withstood battle damage with practically no shock failures associated with the effects of welding.

BIBLIOGRAPHY

1. *The Alloying Elements in Steel,* E. C. Bain, American Society for Metals, 1939.
2. *Tensile Strength and Composition of Hot-Rolled, Plain-Carbon Steel,* C. F. Quest and T. S. Washburn, American Institute of Mining & Metallurgical Engineers, Technical Publication 1182, 1940.
3. *Copper Steels,* C. T. Greenidge and C. H. Lorig, The Iron Age, February 15, 1940.
4. *Properties of Carbon and Alloy Steel Tubing for High-Temperature, High-Pressure Service,* Technical Bulletin 6D, Babcock & Wilcox Co., 1941.
5. *Technical Data for Refineries,* Bulletin No. 26, National Tube Co., 1942.
6. *Alloy Constructional Steels,* H. J. French, American Society for Metals, 1942.
7. *The National Emergency Steels NE8000 Series,* C. M. Parker, American Iron and Steel Institute, August 1942.
8. *Standard End-Quench Hardenability Test,* Society of Automotive Engineers, rev. 1945.
9. *Weldability, Hot-Rolled vs. Quenched and Tempered Constructional Steels,* S. A. Herres, The Welding Journal, March 1945.
10. *Metallurgical Factors of Underbead Cracking,* S. L. Hoyt, C. E. Sims and H. M. Banta, Metals Technology, June 1945; rep. The Welding Journal Res. Suppl., September 1945.
11. *Calculation of Tensile Strength and Yield Point from the Chemical Composition and Cooling Rate,* I. R .Kramer, P. D. Gorsuch and D. L. Newhouse, American Institute of Mining & Metallurgical Engineers, Technical Publication 2067, 1946.

12. *Digest of Steels for High-Temperature Service,* Steel and Tube Div., Timken Roller Bearing Co., 5th Edition, 1946.
13. *Method for Evaluating and Expressing the Toughness of Steel,* S. A. Herres and A. F. Jones, Metal Progress, September 1946.
14. *A Summary of the Spot Welding of High-Tensile Carbon and Low-Alloy Steels,* W. D. Doty and W. J. Childs, The Welding Journal Res. Suppl., October 1946.
15. *Requirements of Steels for High Temperature Service,* C. L. Clark, Metal Progress, November 1946.
16. *Practical Importance of Hydrogen in Metal-Arc Welding of Steel,* S. A. Herres, Transactions, American Society for Metals, 1947.
17. *Some 1000°F. Steam Pipe Materials,* E. L. Robinson, American Society of Mechanical Engineers, Paper 47–A–74, 1947.
18. *Cold Cracking in the Heat-Affected Zone,* C. B. Voldrich, The Welding Journal Res. Suppl., March 1947.
19. *Steel Products Manual,* Section 10, American Iron and Steel Institute, July 1947.
20. *The Heat Treatment of Spot Welds in Steel Plate,* W. F. Hess, W. D. Doty and W. J. Childs, The Welding Journal Res. Suppl., November 1947.
21. *Metals Handbook,* American Society for Metals, 1948.
22. *A Study of the Properties of 0.5% Chromium and 0.5% Molybdenum Pipe Steel,* R. C. Fitzgerald, A. B. Wilder, G. V. Smith and A. E. White, The Welding Journal Res. Suppl., September 1948.
23. *Alloy Steels and Their Heat Treatment,* Bullens and Battelle, Vol. 3, John Wiley and Sons, Inc., 1949.
24. *SAE Handbook,* Society of Automotive Engineers, published annually.

CHAPTER 30

CHROMIUM IRONS AND STEELS*

GENERAL PROPERTIES

Classification of Chromium Irons and Steels

THIS CHAPTER covers chromium irons and steels containing from 3 to 30% chromium. Steels having less than 3% chromium are classified as low-alloy steels and are covered in Chapter 29.

Straight chromium steels having more than 30% chromium are not covered since they have not yet attained commercial importance. The *straight chromium steels* include the alloys of iron, chromium and carbon with some grades containing small percentages of nickel, tungsten, molybdenum, aluminum, selenium or nitrogen. These are distinguished from the chromium steels which contain nickel in sufficient quantities to make them austenitic or otherwise materially alter their properties. Table 1 lists typical chromium irons and steels in the 3 to 30% range, as classified by the American Society for Testing Materials and the American Iron and Steel Institute. Table 2 lists the properties of these materials.

The name *chromium irons* has been applied by industry to differentiate between the non-hardening types of straight chromium steels and the cutlery grades or other hardening types, which are called steels, but since there is no distinct division, the single term *steels* will be used throughout this chapter.

From the welding standpoint, the chromium steels with carbon contents of 0.07 to 0.15% can be divided into two general groups: hardening and non-hardening. Those in the hardening group include the 3 to 10% chromium steels, with molybdenum, which are primarily bainitic and the martensitic steels having 10 to 14% chromium. These steels all display air-hardening characteristics and show split or suppressed transformations on cooling.

Table 1—Chemical Compositions of Chromium Irons and Steels

ASTM Spec. or AISI Type No.	Chemical Composition, %						
	C, Max.	Mn, Range or Max.	Si, Range or Max.	P, Max.	S, Max.	Cr, Range	Other Elements
A213-T21[a]	0.15	0.30–0.60	0.50	0.03	0.03	2.75–3.25	0.80–1.00 Mo
A213-T5[b]	0.15	0.30–0.60	0.50	0.03	0.03	4.00–6.00	0.45–0.65 Mo
A213-T13[c]	0.15	0.30–0.60	1.00–2.00	0.03	0.03	4.00–6.00	0.45–0.65 Mo
A213-T7[b]	0.15	0.30–0.60	0.50–1.00	0.03	0.03	6.00–8.00	0.45–0.65 Mo
A213-T9[b]	0.15	0.30–0.60	0.50–1.00	0.03	0.03	8.00–10.00	0.90–1.10 Mo
502	0.10	1.00	1.00	0.04	0.03	4.00–6.00	.....
403	0.15	1.00	0.50	0.04	0.03	11.50–13.00	.....
405	0.08	1.00	1.00	0.04	0.03	11.50–13.00	0.10–0.30 Al
410	0.15	1.00	1.00	0.04	0.03	11.50–13.50	.....
414	0.15	1.00	1.00	0.04	0.03	11.50–13.00	1.25–2.50 Ni
430	0.12	1.00	1.00	0.04	0.03	14.00–18.00	.....
431	0.20	1.00	1.00	0.04	0.03	15.00–17.00	1.25–2.50 Ni
442	0.20	1.00	1.00	0.04	0.03	18.00–23.00	.....
443	0.20	1.00	1.00	0.04	0.03	18.00–23.00	0.90–1.25 Cu
446	0.35	1.00	1.00	0.04	0.03	23.00–27.00	0.25 max. N

[a] ASTM Specification A200 Grade 5 is similar.
[b] ASTM Specifications A158 Symbols P5a, P16 and P17, and A200 Grades 7, 8 and 9 are similar.
[c] ASTM Specification A158 Symbol P5c is similar.

* Prepared by a committee consisting of E. C. Chapman, Combustion Engineering-Superheater, Inc., *Chairman;* R. W. Emerson, Pittsburgh Piping & Equipment Co.; E. R. Seabloom, Crane Co.

Table 2—Mechanical Properties of Annealed Chromium Steels at Room Temperature

ASTM Spec. or AISI Type No.	Alloy	Tensile Strength, Psi., Min.	Yield Point, Psi., Min.	Elongation in 2 In., %, Min.	Brinell Hardness, Max.	Coefficient of Thermal Expansion per °F.[a]
A213-T21	2¾–3½ Cr, 0.90 Mo	60,000	25,000	30	163	7.8×10^{-6}
A213-T5	4–6 Cr, 0.50 Mo	60,000	25,000	30	163	7.2×10^{-6}
A213-T13	4–6 Cr, 0.50 Mo, Si	60,000	25,000	30	163	7.3×10^{-6}
A213-T7	6–8 Cr, 0.50 Mo	60,000	25,000	30	179	6.9×10^{-6}
A213-T9	8–10 Cr, 1.00 Mo	60,000	25,000	30	179	7.0×10^{-6}
502	4–6 Cr	65,000	25,000	30	150	7.2×10^{-6}
403	11½–13 Cr	75,000	40,000	30	150	6.4×10^{-6}
405	11½–13 Cr, 0.20 Al	70,000	45,000	35	150	6.7×10^{-6}
410	11½–13½ Cr	75,000	40,000	30	150	6.4×10^{-6}
414	11½–13½ Cr, 1.87 Ni	100,000	80,000	22	217	6.7×10^{-6}
430	14–18 Cr	75,000	40,000	35	160	6.2×10^{-6}
431	15–17 Cr, 1.87 Ni	125,000	95,000	20	250	6.8×10^{-6}
442	18–23 Cr	85,000	45,000	20	175	6.4×10^{-6}
443	18–23 Cr, 1.00 Cu	90,000	50,000	20	187	6.4×10^{-6}
446	23–27 Cr, 0.25 N	85,000	55,000	25	180	6.4×10^{-6}

[a] Mean coefficient of thermal expansion 32 to 1000°F.

Split transformations usually result in some ferrite and pearlite along with bainite and/or martensite. Steels in the nonhardening group are ferritic and contain from 18 to 30% chromium. These do not harden, even when cooled rapidly from the welding heat, since with normal carbon contents they generally have no critical transformations.

Between these two groups, there is a range of steels having 14 to 18% chromium that are partly martensitic and partly ferritic, their behavior depending upon the chromium content with respect to the amount of carbon.

Chromium steels have numerous applications but are primarily utilized for resistance to oxidation and corrosion, the operating temperature and corrosive environment determining the steel to use. Resistance to oxidation increases with the percentage of chromium, as illustrated in Fig. 1, which shows the loss in weight in ½-in. cubes by oxidation at 1000°C. (1830°F.) for 48 hrs., and the same is generally true for corrosion resistance, as shown in Table 3.

The lower chromium grades, from 3 to 10% Cr, as a rule have molybdenum additions ranging from 0.50 to 1.50%, as indicated in Table 1, to impart creep strength and resistance to temper embrittlement and are therefore used extensively at high temperatures, mostly in oil refinery service where oxidation and corrosion are rather moderate. The 3 to 5% chromium, 0.5 to 1% molybdenum alloys are also employed to a lesser degree in steam superheaters and in steam power plant piping operating at temperatures up to 1150°F. While in such applications the chromium contributes to oxidation resistance, it also offsets the danger of graphitization in the weld and heat-affected zones, experienced with some of the carbon-molybdenum steels, by producing a spheroidized or stable carbide structure.

Steels having chromium in the range of 10 to 14% have a wide field of usage. Since they are of the stainless type and have good mechanical properties combined with excellent resistance to erosion, often encountered with high velocity fluid flow,

Table 3—Results of Corrosion Tests of Chromium Steels in Nitric Acid

Thickness	Analysis Cr	C	Mn	Si	Ni	Heat Treatment, °F.	Average Penetration, In./Month
⅛-in. plate	17.2	0.08	0.44	0.37	0.15	1425, furnace cooled	0.00192
½-in. weld and plate	17.1	0.10	0.48	0.45	0.08	1425, furnace cooled	0.00198
½-in. weld and plate	17.1	0.10	0.48	0.45	0.08	1425, water quenched	0.00209
⅝-in. plate	15.3	0.09	0.42	0.47	0.06	1425, furnace cooled	0.00409
⅝-in. weld and plate	15.5	0.08	0.48	0.41	0.10	1425, furnace cooled	0.00395
⅝-in. plate	15.3	0.09	0.42	0.47	0.06	1425, water quenched	0.00388
¾-in. weld and plate	12.1	0.10	0.37	0.43	0.15	1425, furnace cooled	0.01655
¾-in. plate (0.22 Al)	12.6	0.08	0.45	0.37	0.10	1425, water quenched	0.01713

NOTES: Size of corrosion test samples, ⅞ x 1⅞ x ⅜ in. Tested for five 48-hr. periods in boiling 65% nitric acid. Acid renewed for each period. Penetration rates given are average for five periods.

they are suitable for turbine blading and valve seat facings.

Of the steels in the 14 to 18% chromium group, the group of 15 to 16% chromium steels is an important one because of the corrosion resistance to nitric acid of these steels and because they are the least difficult of the straight chromium steels to weld.

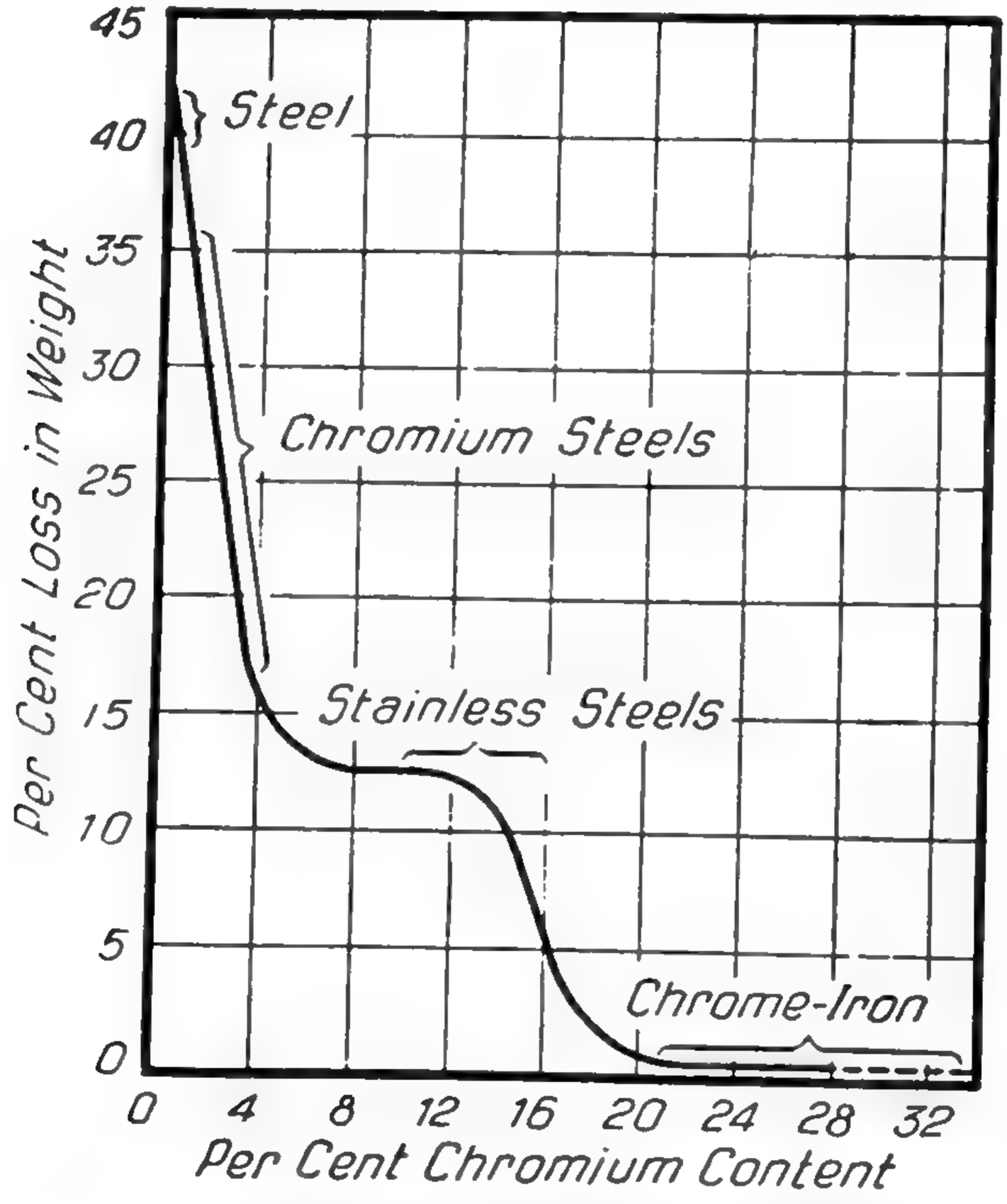

Fig. 1.—Loss of Weight in 1/2-In. Cubes by Oxidation at 1000°C. for 48 Hr.

The 18 to 30% chromium steels, particularly in the 23 to 30% range, are primarily employed for resistance to oxidation at elevated temperatures. They are also used in some catalytic refining applications instead of the more weldable chromium-nickel steels, because nickel is believed to have a deleterious effect on certain chemical processes.

Metallurgical and Mechanical Properties

The 3 to 10% chromium steels with 0.50 to 1% molybdenum and the 10 to 14% straight chromium steels are air-hardening, that is, the weld and heat-affected zones harden when air cooled from the welding heat. The hardenability and thermal sluggishness increase with increasing chromium, carbon and molybdenum, thus producing split or suppressed transformations on cooling from high temperatures. The amount of hardening is somewhat dependent upon the rate of cooling, particularly with the 3 to 10% chromium-molybdenum steels. With carbon contents below about 0.08%, no, or very weak, suppressed transformations occur at slow cooling rates (see Fig. 2) whereas with more rapid cooling, such as in welding, split or suppressed transformations are encountered as shown in Fig. 3. When the carbon content is above about 0.10%, the transformations are generally suppressed regardless of cooling rate, as illustrated by Figs. 4 and 5. There is a minor exception to this last statement. The 8 to 10% chromium steels, because of their lower carbon contents and the combined effect of chromium and molybdenum, particularly the latter, contain untransformed (delta) ferrite, thus reducing the thermal sluggishness

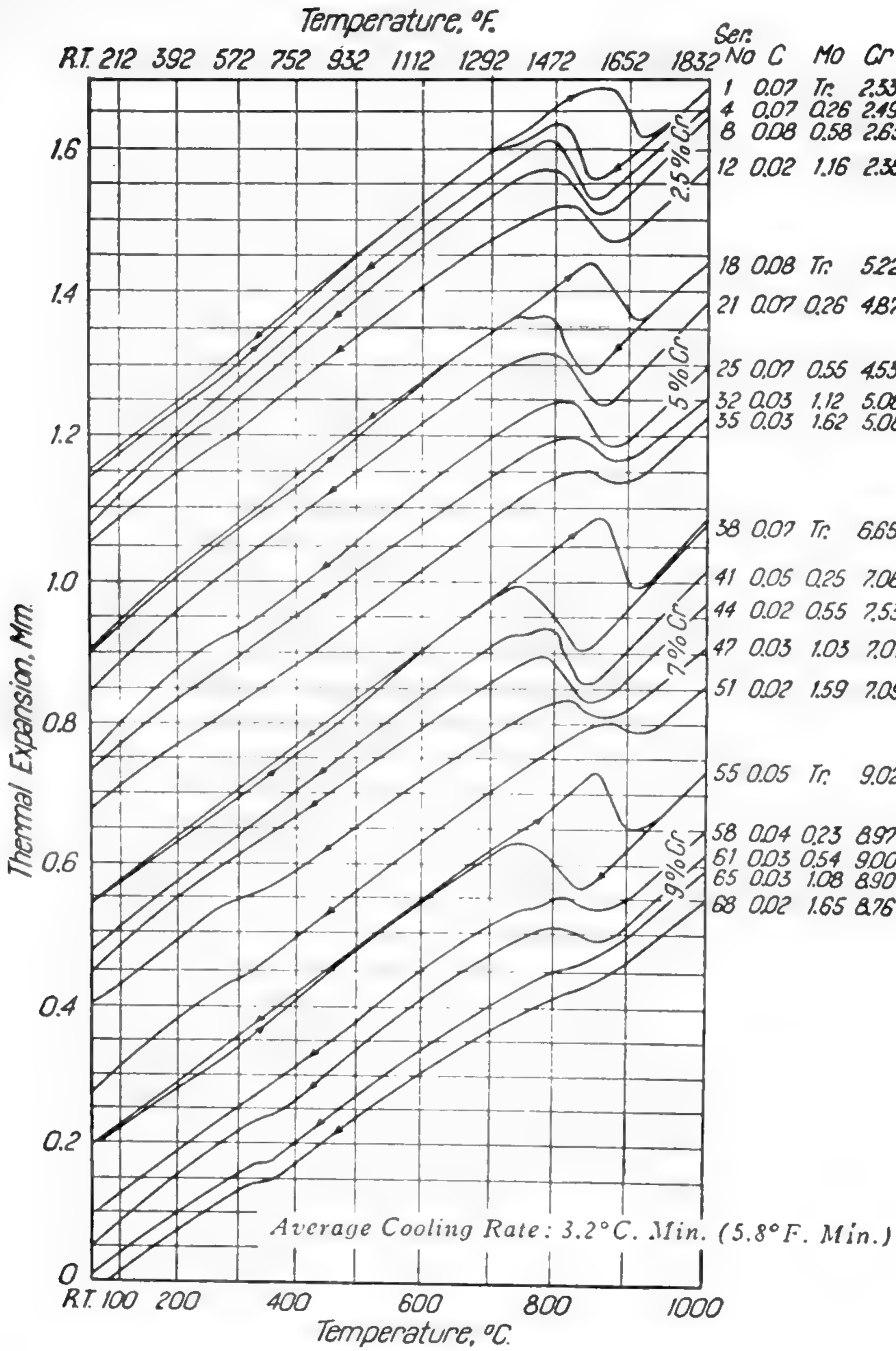

Fig. 2.—Thermal Cooling Curves of Low-Carbon Chromium-Molybdenum Steels (Slow Cooling Rate)

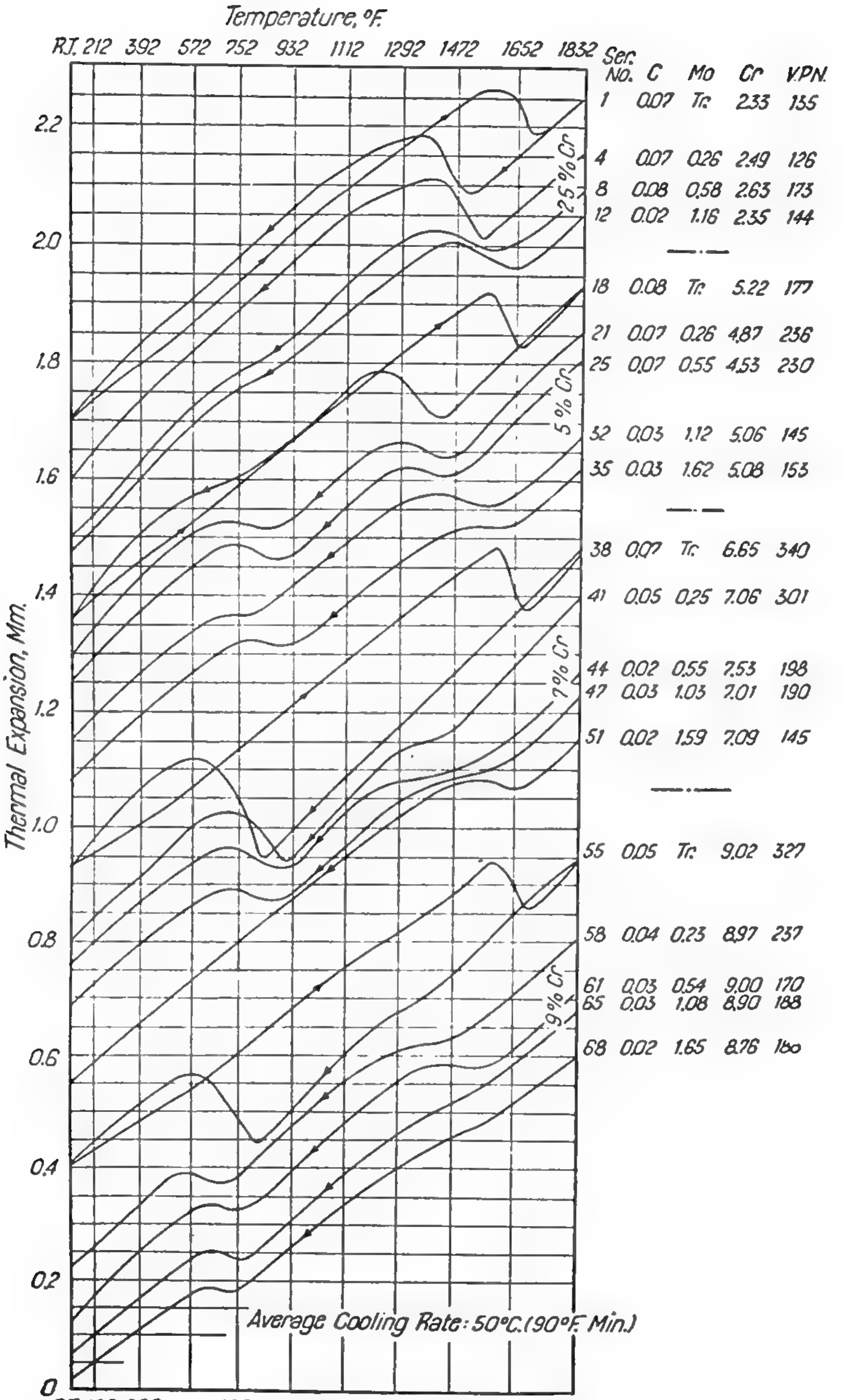

Fig. 3.—Thermal Cooling Curves of Low-Carbon Chromium-Molybdenum Steels (Rapid Cooling Rate)

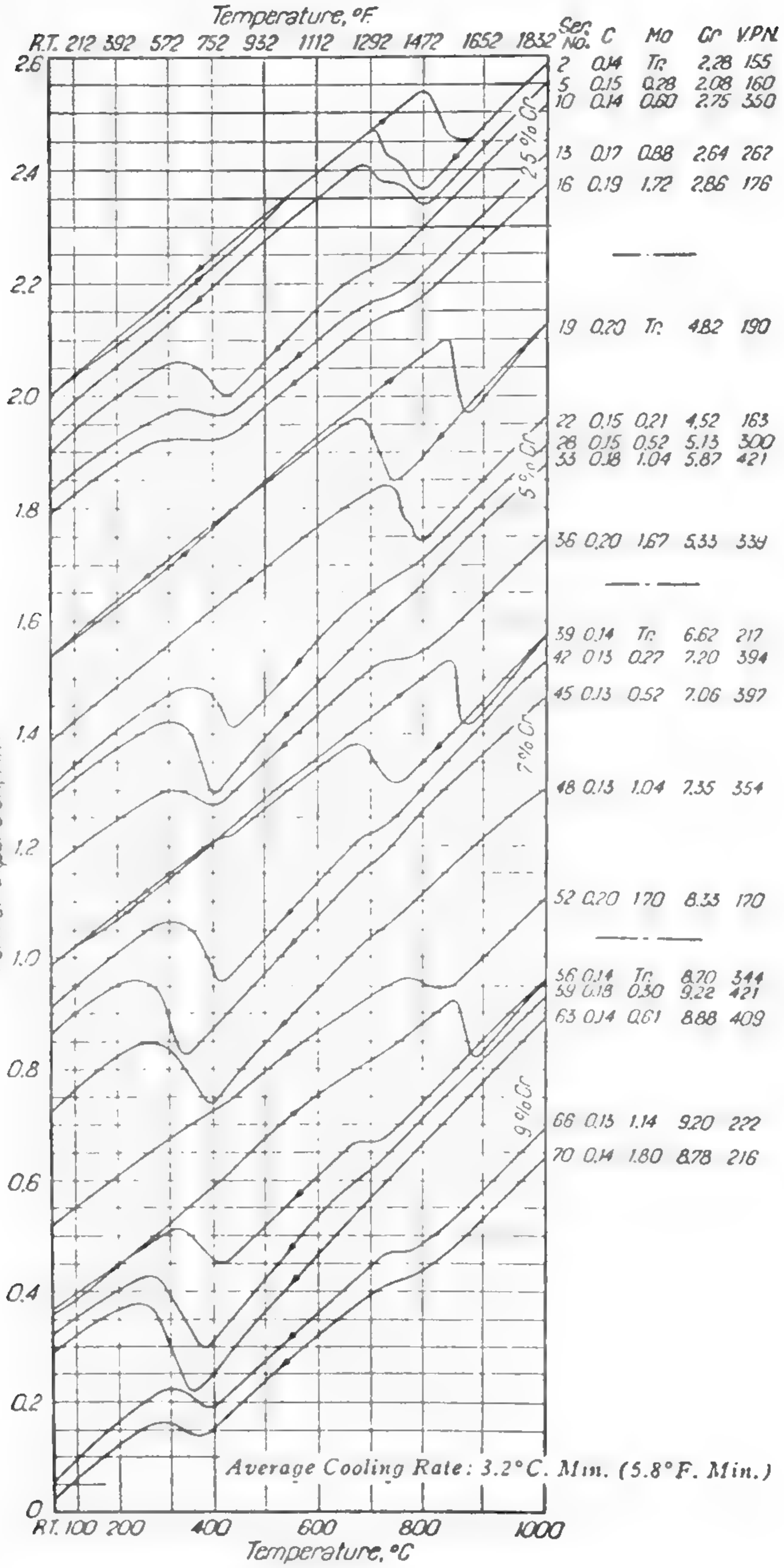

Fig. 4.—Thermal Cooling Curves of High-Carbon Chromium-Molybdenum Steels (Slow Cooling Rate)

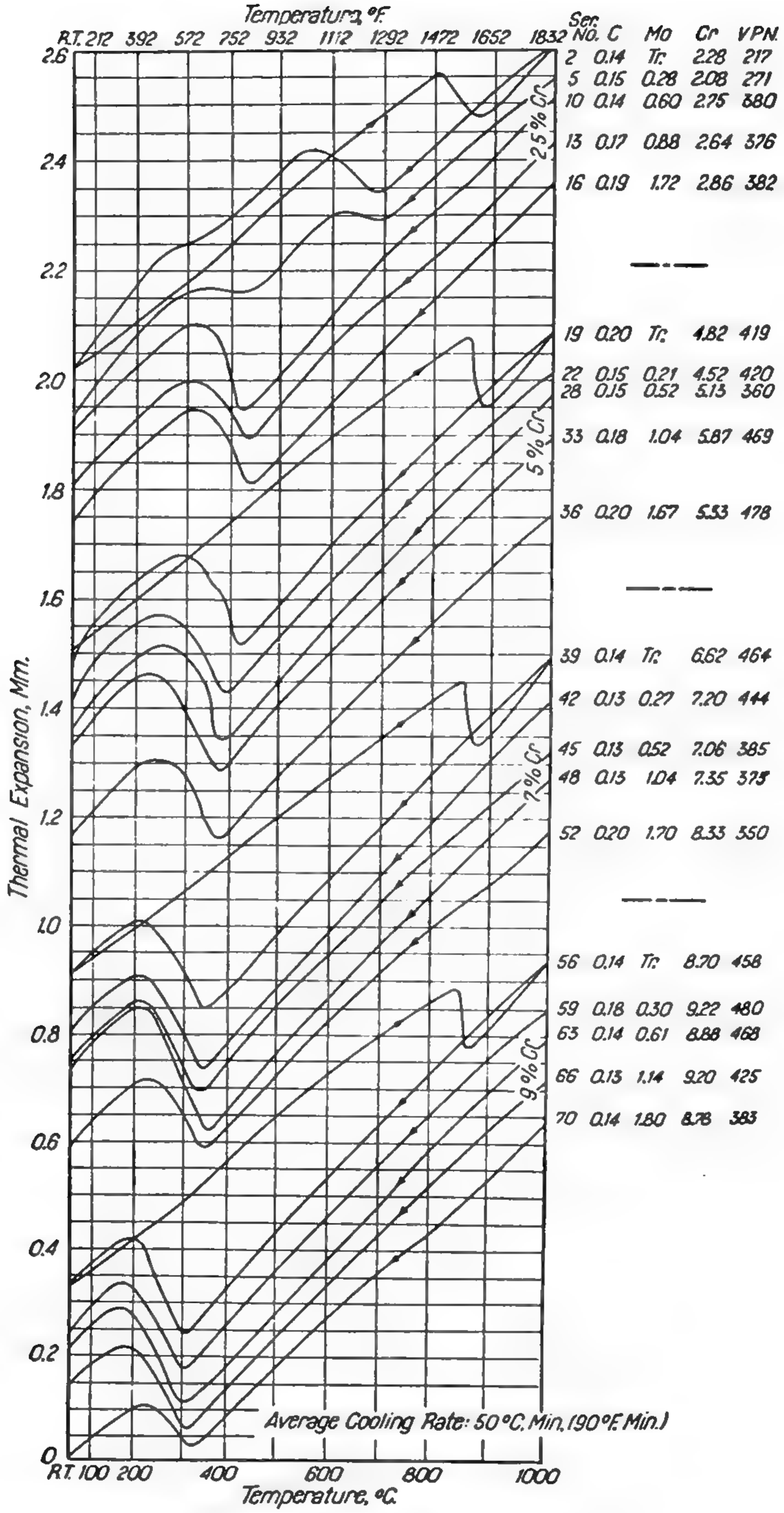

Fig. 5.—Thermal Cooling Curves of High-Carbon Chromium-Molybdenum Steels (Rapid Cooling Rate)

and hardenability. The 10 to 14% straight chromium steels are decidedly air-hardening and display very marked suppressed transformations even at slow cooling rates (see Fig. 6). The important thing about suppressed transformations is that they occur at temperatures at which the metal is no longer plastic, creating internal stresses which, unless relieved by suitable techniques, may result in cracked welds.

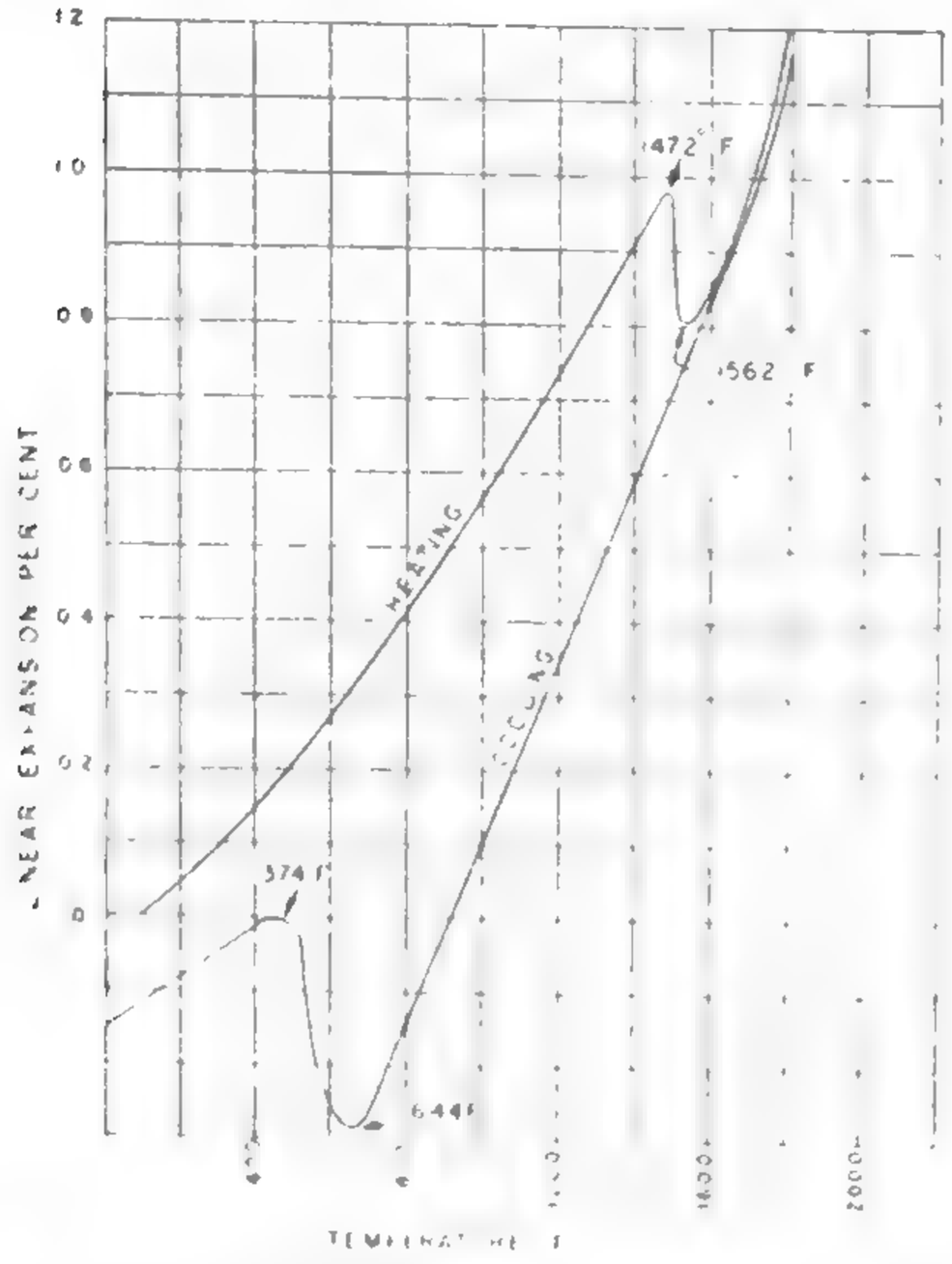

Fig. 6.—Thermal Cooling Curve for 12% Straight Chromium Steel with 0.12% Carbon (Slow Cooling Rate, 5.8°F. per Min.)

Carbide-forming agents, such as columbium and titanium, have been used to some extent, mostly on 4–6% chromium, ½% molybdenum steels. Both of these elements have a high affinity for carbon and tend to form stable carbides. Thus, the carbon is made inactive and pronounced hardening cannot result unless the temperature is sufficiently high to permit these carbides to enter into solid solution.

Chromium is also a strong ferrite former and as the chromium is increased above 14%, the alpha-gamma transformation is gradually eliminated so that a single-phase alloy of ferrite finally results at about 17 to 18% chromium with carbon under 0.10%. Iron-chromium alloys having 14 to 18% chromium are called *transition alloys*. The proportion of martensite and ferrite in a transition alloy varies with the composition, carbon having the greatest influence in promoting martensite. Referring to the constitutional diagram in Fig. 7, which shows the structures in steels of various carbon and chromium contents in ½-in. cubes air cooled from 1830°F., the effect of carbon on extending the martensitic range toward the higher chromium alloys is apparent. The steels in the transitory group having 14 to 18% chromium do not harden to as great an extent as the 10 to 14% chromium steels nor do they develop grain growth with resultant brittleness as do the 18 to 30% chromium steels. However, there is no distinct line of demarkation in behavior of this group; that is, those having lower chromium contents will act similar to the martensitic grades and those having higher chromium will display characteristics somewhat like the ferritic types.

The 18 to 30% chromium steels are entirely ferritic and generally do not have critical points. The maximum carbon contents specified for the commercial grades are higher than for the other types of chromium steel but this does not cause perceptible air-hardening. Higher carbon is beneficial in the ferritic steels for reducing grain size and brittleness, whereas in the martensitic and bainitic types carbon should preferably be under 0.10%.

Since the ferritic steels are normally single-phase alloys, except for small amounts of carbide, they do not respond to heat treatment. Therefore, with the exception of mechanical working, there is no possibility of refining coarse grains shown in Fig. 8, which result from welding temperatures in both the heat-affected base material and the multilayer deposited metal. The weld shown in Fig. 8 was made without preheat but stress relieved at 1480°F. The columnar grains of ferrite reduce the ductility and impact strength of the steel. These steels, without grain refinement, are extremely notch sensitive and stress raisers, such as sharp re-entrant angles, undercuts and surface irregularities, should be avoided. A hard and brittle constituent identified as sigma phase may also develop on prolonged heating, particularly in stressed or worked metal. Ferritic chromium steels are usually ductile at elevated temperatures but are brittle below 200°F. if the sigma

phase constituent is present or if the grain has not been refined. Most welds in the higher straight chromium steels are made with E310, E309 or 27–4 chromium-nickel austenitic or partially austenitic electrodes to produce better ductility in the deposited metal than obtained with straight chromium electrodes. However, some grain growth will occur in the base metal, as shown in Fig. 9 which illustrates a weld made with a preheat of 450°F., resulting in a broadened heat-affected zone and increased grain size. Usually 0.10 to 0.25% nitrogen is added to the 23 to 30% chromium steels to refine the grain structure and inhibit grain growth at high temperatures, but it does not appear to improve impact properties in the weld metal appreciably.

The mechanical properties of annealed chromium steels at room temperature are listed in Table 2. In steels having between 3 and 14% chromium the tensile strength, yield point, elongation and hardness can be varied by heat treatment, but in the higher chromium steels these properties can only be altered by mechanical hot or cold working. Since all of these steels are frequently used on the basis of their high temperature creep properties rather than their mechanical properties at room temperature, reliable creep data should be consulted. The 23 to 25% chromium steels are subject to embrittlement on prolonged heating in the range of 1025 to 1300°F. which is associated with sigma phase. Extended heating at from 700 to 1000°F. or slow cooling through this range also causes brittleness and some authorities believe the effect is similar to the temper embrittlement which occurs in lower alloy steels upon slow cooling after tempering. The ductility of these steels may be restored by proper annealing.

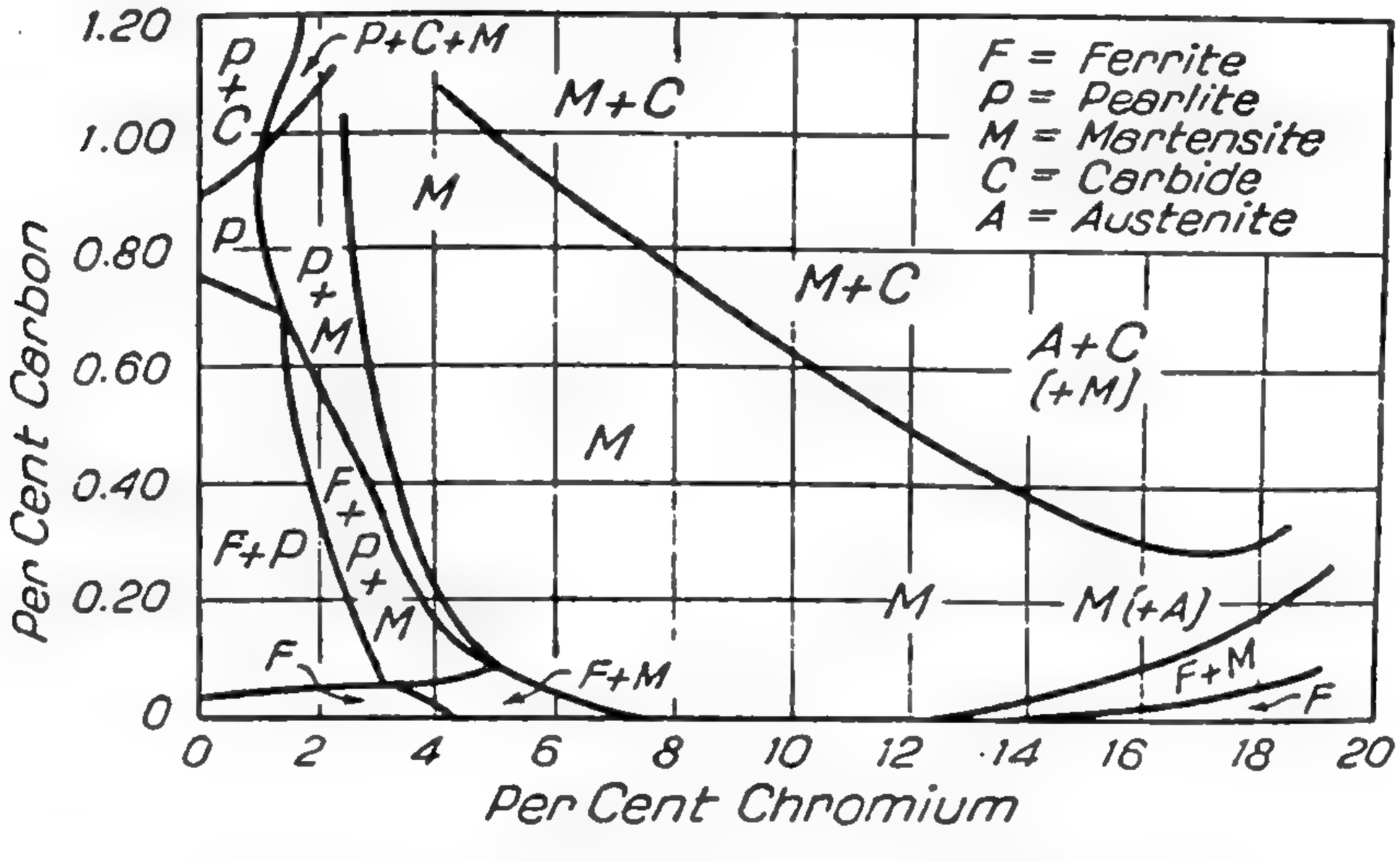

Fig. 7.—Constitutional Diagram for Chromium Steels

HOW TO WELD

General

All of the welding processes in general use for carbon steels and other alloy steels are also applicable for welding all types and grades of chromium steels. With a few exceptions the procedures used with these processes for the chromium steels follow closely those employed for the other steels. Several general basic principles apply to the welding of these steels as a group which if understood will be helpful in appreciating the recommended welding procedures for the various classes of these steels.

Protection Against Oxidation.—All welding processes suitable for the chromium steels involve the use of a non-oxidizing atmosphere for the purpose of excluding air from the liquid metal and/or the provision of a suitable flux for assisting in removal of the chromium oxide from the liquid weld metal before it solidifies. Chromium oxide is an extremely refractory material which melts

at a temperature (3582°F.) far above the melting point of steel (2700°F.) or of iron oxide (2850°F.). There are but few materials which serve as effective fluxes for the removal of chromium oxide during welding, hence all fluxes employed for other steels may not be suitable for the chromium steels unless they contain materials with a capacity for dissolving chromium oxide. This applies to the coverings of electrodes for arc welding as well as

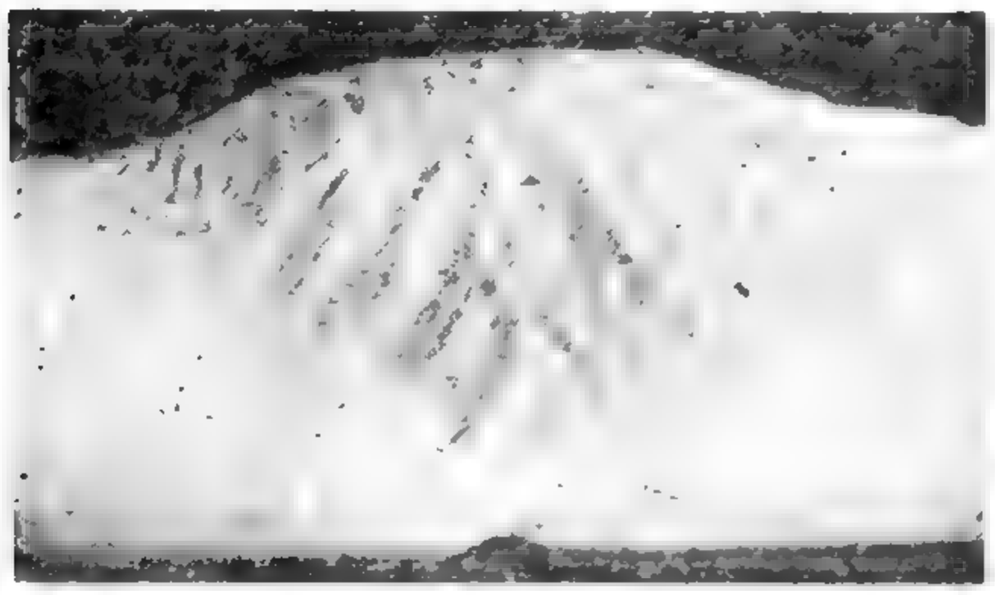

Fig. 8.—Macrograph of Weld in 27% Straight Chromium Steel with Weld of Similar Analysis

to fluxes for gas or submerged arc welding. However, a flux is seldom used for welding these materials with the atomic hydrogen or inert-gas metal-arc process since the atmospheres employed have proved sufficiently effective for preventing excessive oxidation. The fluorides, such as calcium or sodium fluoride, are probably the most commonly used ingredients in fluxes and coatings for dissolving chromium oxide, although others have been used and are said to be satisfactory. Materials such as cryolite or cryolith are frequently used as a source for the fluorides in order to minimize the irritating fluorine fumes which these materials emit upon heating.

Non-oxidizing or inert gas protection is frequently provided around flash welding operations, to prevent the formation of chromium oxide which is difficult to exclude during upsetting.

Preheating and Interpass Temperature Control.—Preheating and maintaining the proper temperature until the weld is completed is the safest practice for welding the chromium steels. The amount of preheat required for the different groups of these steels is given under the discussions on each group below. There are exceptions to this preheating requirement, such as in certain cases when austenitic filler metal is used or when welding thin materials, but each case should be carefully judged on the basis of the conditions and requirements involved. The geometry of the weldment, filler metal composition, groove design, welding process employed and facilities for preheating must all be considered when deciding whether or not to preheat. The rule *when in doubt, preheat*, is a good one to follow with these materials.

Preheating these steels: (1) reduces the as-welded shrinkage stresses by lowering the temperature differential between base and weld metal, and by lowering the yield point of the material; (2) reduces the as-welded hardness of the hardenable grades appreciably, but only if the preheat is high enough to accelerate metallurgical transformations (above about 600°F.); (3) reduces the tendency to crack by reducing notch sensitivity at the preheating temperature. This last effect is the principal advantage of preheating the high chromium, non-hardenable, ferritic steels. The preheat required to toughen these steels is very low as will be shown below.

Filler Metal.—The welds in chromium steel weldments are usually subjected to the same service environment and conditions as the base metal and should have at least equivalent properties to withstand all service requirements. Two

Fig. 9.—Macrograph of 25–20 Chromium-Nickel Weld in 27% Straight Chromium Steel Showing Broadened Heat-Affected Zone and Increased Grain Size in Adjacent Base Metal

general classes of filler metals are employed: (1) straight chromium filler metal duplicating as nearly as practical the base metal analysis, including the modifying elements such as molybdenum and (2) austenitic filler metal having chromium and nickel contents sufficient and properly proportioned to allow for dilution, which results from mixing with the base metal, so that the analysis of

the final deposit will provide an acceptable amount of austenite. Neither the hardenable straight chromium nor the nonhardenable ferritic filler metals are used unless the weldment is to receive a postheat treatment. Hence, practically all field welding is done with austenitic filler metal. Field welding of any kind is usually not permitted for the hardenable grades when local heat treatment is not applied or where these materials are to be subject to stress in service and the operating temperature is insufficient to adequately heat treat before the stress load is applied. Filler metal of the straight chromium analyses offers the advantage of providing a weld having the same coefficient of thermal expansion as the base metal and such welds can be more nearly completely stress relieved than welds made with austenitic filler metal. The use of austenitic filler metal with its higher coefficient of thermal expansion results in a weld which cannot be effectively stress relieved (except when operating continuously at a uniform elevated temperature where plastic flow can take place over a long period of time) and the fatigue effect of thermal stresses under cyclic temperature operation should be considered.

Fabrication problems are considerably lessened by the use of austenitic filler metal. Such metal does not harden upon quenching and it possesses a high degree of notch toughness, both of these properties being favorable to welding by lessening the possibility of cracking. While preheating is usually desirable it may often be omitted, particularly if the weldment is to receive a postheat treatment. If no postheat treatment is to be administered, preheating is often done for the sole purpose of keeping the residual stresses as low as possible. A stabilized austenitic filler metal is recommended when maximum corrosion-resisting properties are desired. The heat treatment required for returning carbides into solution in the austenite of unstabilized steels involves rapid cooling from a high temperature which is not suitable for base metal having below about 17 or 18% chromium, depending on the carbon content. When the welds are to be used in a corrosive environment, consideration should be given to the possibility of electrolytic corrosion, which results from the galvanic current produced by dissimilar metals in contact when exposed to an electrolyte. This problem requires separate consideration for each individual application since in many environments electrolytic corrosion has not proved to be a problem with these material combinations.

The heat effect of welding is the same regardless of the filler metal analysis so that from the standpoint of mechanical properties in the as-welded condition, the heat-affected zone is usually the weakest point in a joint welded with austenitic filler metal. The choice of preheat temperature and whether or not to postheat are dependent on the capacity of this heat-affected zone to withstand the fabricating and service stresses to which it is to be subjected.

Design.—There are no design limitations which must be observed for these particular materials. As in the case of any material where the danger of cracking exists, butt joints welded from both sides, which can be radiographed, are preferred to fillet welds. Whenever possible, stress concentrations should be avoided on higher chromium ferritic welds. Groove shapes follow closely those used for other steels, although they are sometimes modified to suit the characteristics of a particular electrode. The straight chromium steels have the same general design limitations as other materials when the weldments must be heat treated and radiographed. The weldment must either have sufficient structural strength to resist excessive deformation at the heat-treating temperature or the design must permit the use of temporary bracing for providing the necessary support. For radiographing, the back side of the welded joint must be accessible in order that the film holder can be placed in position.

3 to 10% Chromium Steels

Steels having 3 to 10% chromium are intensely air-hardening and for this reason as low a carbon content as possible with a maximum of 0.10% is beneficial and this maximum is frequently specified when ordering material (see Figs. 2 and 4 for effect of carbon on the transformations). Filler metal of the same composition as the base material when properly heat treated has excellent mechanical properties in every respect, including good impact and fatigue strength. Preheating and interpass temperature control should be considered as mandatory. The hardness of the weld, as deposited, is affected

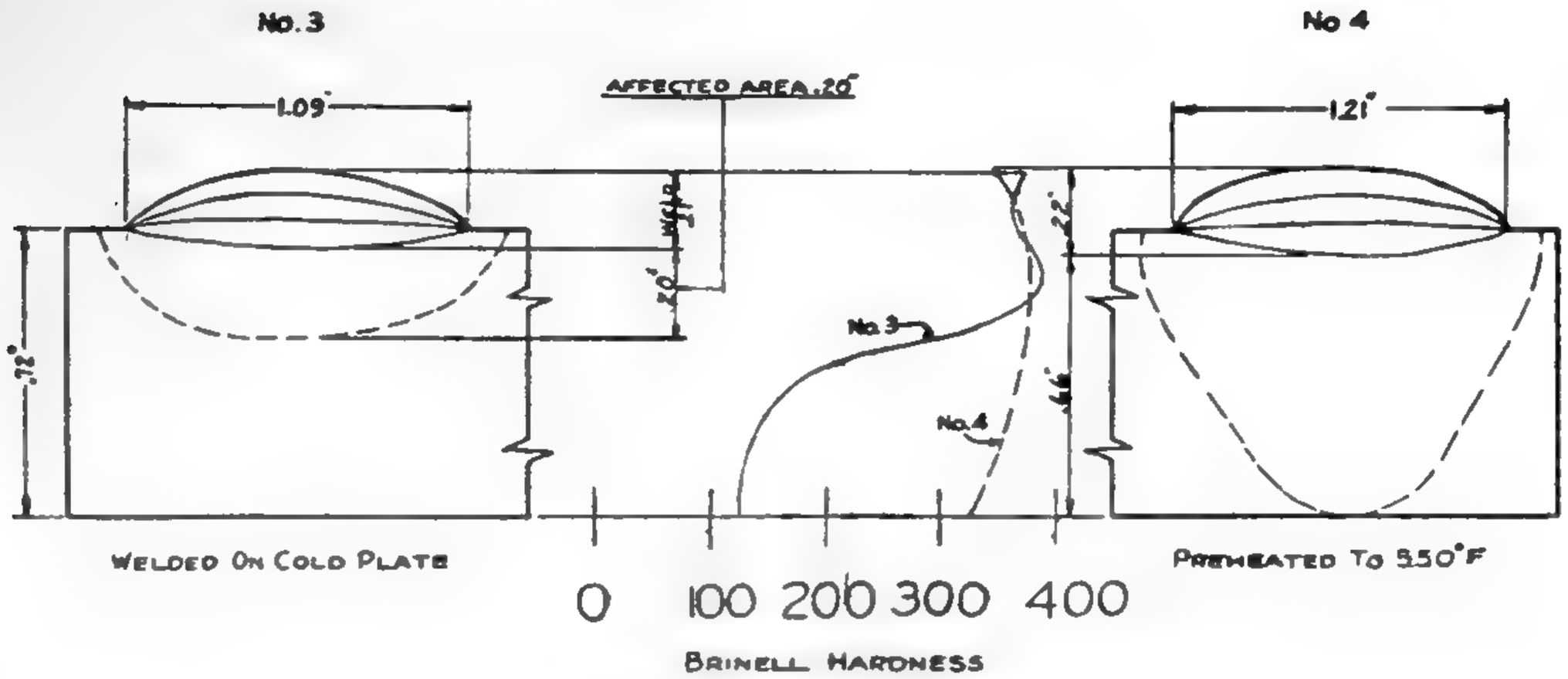

Fig. 10.—Hardness of Unannealed Deposited Metal and Heat-Affected Zone in 4–6 Cr Steel
Weld made with three superimposed layers.

but little by preheating unless the preheat temperature is above 600°F., and a preheat of this magnitude is frequently impractical. Increasing the preheat temperature results in a deeper heat-affected zone (see Fig. 10), but other benefits make the use of the highest practical preheat temperature desirable. Experience has shown that weldments of these steels should be heat treated without allowing the preheat temperature to drop after welding. Such practice often entails several interstage heat treatments, but their cost is often justified considering the cracking hazard which exists if the weldment is allowed to cool before heat treatment.

A large amount of piping made of steel within this range has been used in oil refinery service for strength and resistance to corrosion at high temperatures. Much of this piping has been welded with austenitic electrodes and has given very satisfactory service. Some of it has been put into service without any heat treatment, but this practice is not recommended. Superheater tubing and headers in steam generating units have utilized lesser amounts, but this is considered a highly important application for this material. Flash welding is a commonly used method for joining superheater tubes. The addition of titanium or columbium to the tube material for the purpose of combining with the carbon and thus shortening the heat treating time required for flash-welded joints has proved to be a means for speeding production. The use of these non-hardening agents in filler metal has not received wide approval because of the very close analysis limits which must be held. If the titanium or columbium content materially exceeds the amount required to completely combine with all of the carbon, a ferritic weld having a columnar structure and low notched impact strength, will be obtained.

The results of mechanical tests made on a typical weld in 5% chromium plate are shown in Table 4. Throughout the

Table 4—Test Data of Annealed 4–8% Chromium, 0.5% Molybdenum Weld and Plate

	Thickness, In	Analysis			Mechanical Properties				
		Cr	C	Mo	Tensile Strength, Psi.	Yield Point, Psi.	Elongation in 2 In., %	Reduction in Area, %	Bend Elongation, %
Weld	$\frac{3}{4}$	4.14	0.12	0.44	85,250	58,250	26	40	63
Plate	$\frac{3}{4}$	5.10	0.10	0.53	74,250	33,000	33	74	..

NOTE: Charpy keyhole notch impact value for weld metal, 20 to 30 ft.-lb.

range of 3 to 10% chromium, the maximum hardness of the weld and heat-affected zone which results from rapid cooling is very nearly the same, although somewhat less difficulty has been experienced with welding steels having from 3 to 3.5% chromium. The mechanical properties at room temperature after heat treatment are practically the same throughout the range. The same welding procedures are recommended for any analysis within this range.

11 to 14% Chromium Steels

Chromium steels having 11 to 14% chromium may be considered similar to the 3 to 10% chromium steels as regards air-hardening properties and the welding procedures for welding both groups are identical. In considering those properties which influence weldability, the chief difference between the two groups probably lies in the lower thermal conductivity of the higher chromium steels. An increase in chromium sharply decreases thermal conductivity (see Fig. 11) and this trend, although favorable to welding in most cases, can have a harmful effect in others. Additional information on this subject is furnished in the discussions of the various processes. Probably the greatest usage for these steels has been for linings of pressure vessels employed in oil-refining processes; they have also been used as the cladding of clad steels which have gone into pressure vessels for the same type of service (see Chapters 37A and 37B). Such linings are usually very light and since the joints are usually welded with austenitic electrodes, no preheat is employed.

These steels are seldom used for strength at high temperatures because of their low creep strength, and molybdenum is not added for improving creep strength because this element promotes the formation of ferrite with its characteristic notch sensitivity. Aluminum has proved to be an effective non-hardening agent which does not appreciably affect other important properties of the material. Figure 12 shows a comparison between the hardness in the heat-affected zones of a 12.4% chromium steel having 0.09% carbon and a steel of approximately the same analysis to which 0.26% aluminum has been added. Where preheating or final heat treatment is not used, this non-hardening steel may be employed to advantage.

Because of the common applications for these steels, most of the welding has been done with austenitic filler metal. However, weld metal having the same analysis as the base metal exhibits excellent properties after heat treatment as can be determined from the data in Table 5.

Reference to Fig. 1 will show that steels within this group have been given the popular name of *stainless steel* and resist atmospheric corrosion indefinitely. The cutlery steels having a higher carbon content, also fall within this range of chromium, but there is seldom reason to weld them. The high-carbon chromium steels are also used for dies which sometimes

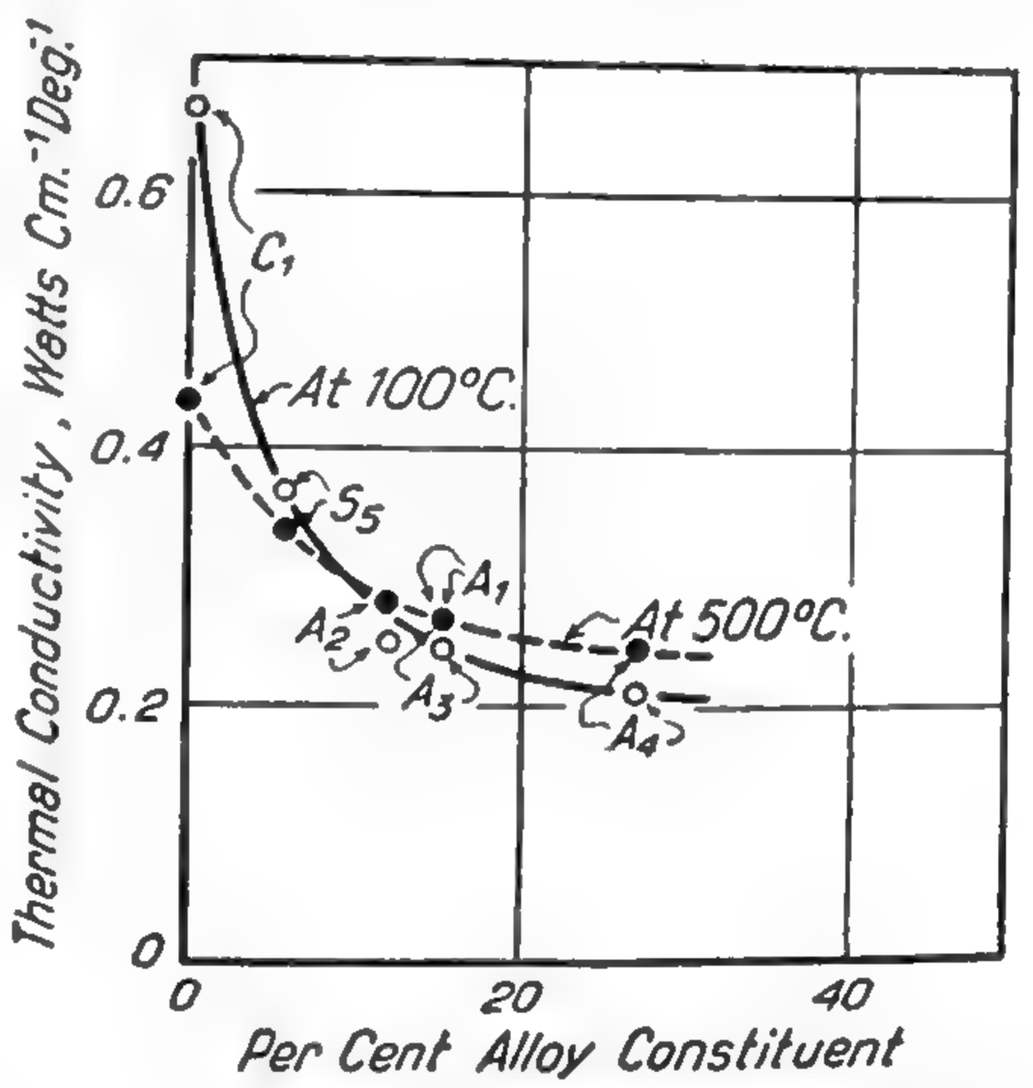

Fig. 11.—Decrease in Thermal Conductivity with Increasing Chromium

must be repaired by welding; this, of course, can be done by preheating to a sufficient temperature.

14 to 18% Chromium Steels

Steels having 14 to 18% chromium may be either a martensitic steel with 14% chromium, which quenches to a very high hardness, or a completely ferritic, single-phase alloy with 18% chromium which has no transformation points. An alloy close to the middle of this range having from 15 to 16% chromium has been used in very large quantities in ammonia oxidation units for the manufacture of nitric acid, in vessels for the storage of this acid and in tank cars for its transportation.

The materials within this narrow range, as would be expected in a transition alloy, have physical and corrosion-resist-

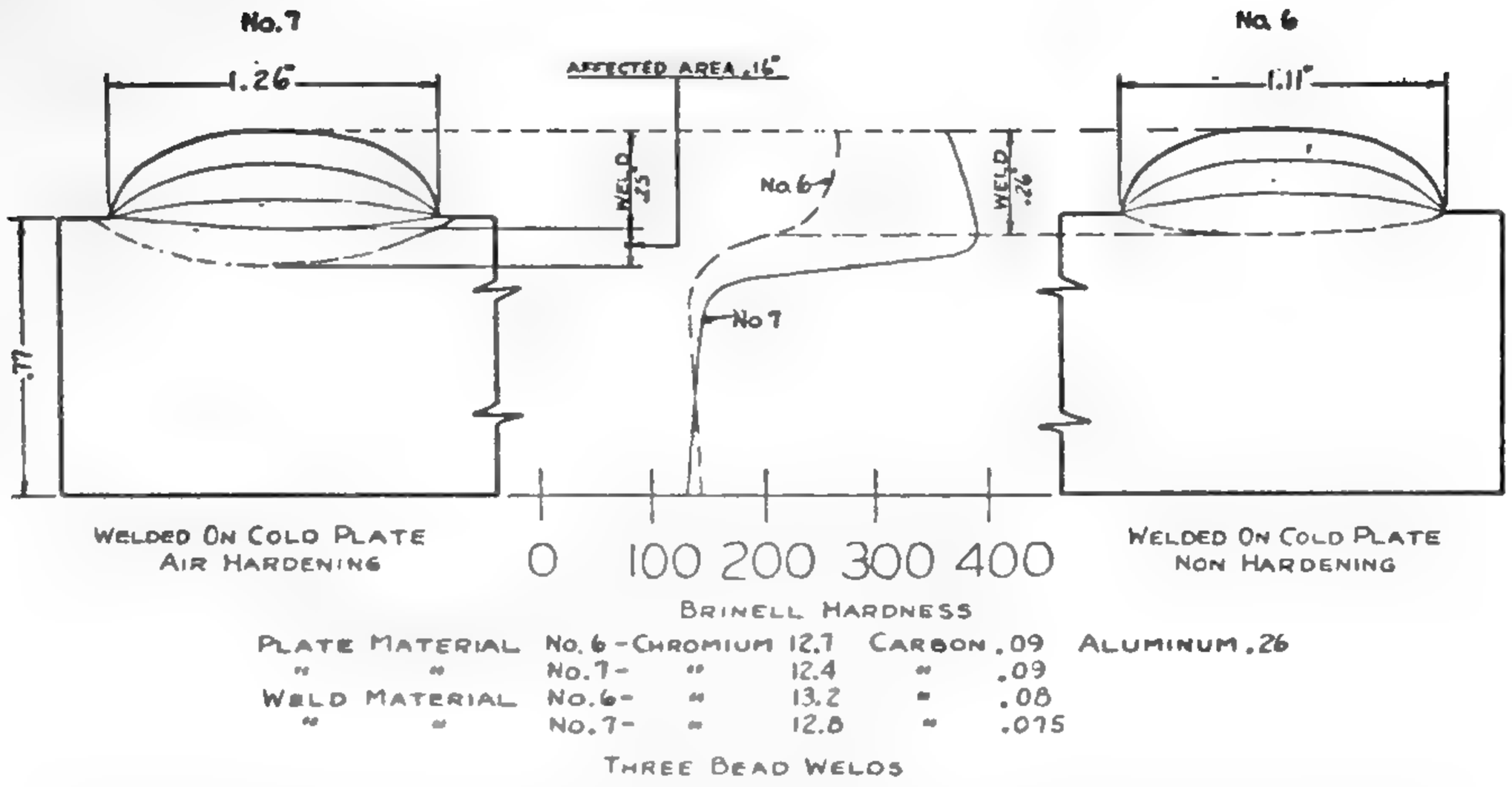

Fig. 12.—Hardness of Unannealed 12–14% Chromium Welds and Heat-Affected Zone
Weld made with three superimposed layers on the hardening and non-hardening types for comparison.

ing properties averaging those at the top and bottom of the range. They are neither so notch sensitive as the 18% chromium steels nor so air-hardening as the 14% chromium steels. The mechanical properties of the steels in this group are very close to the borderline of acceptability for use in pressure vessels, but they have given most satisfactory service in such vessels for many years. This equipment has been largely welded with covered electrodes depositing the same analysis as the base material. A study of the notched-bar impact properties of these steels (Fig. 13) as they are affected by temperature will show the reason for preheating materials within this chromium range before welding and should also relieve anxiety over the notch sensitivity of the welds when operating above 150°F. The transition from a brittle cleavage fracture to a ductile one occurs between temperatures of about 100 and 250°F. and when the fracture is completely fibrous the notched-bar impact strength is excellent. Shifting of this transition range to a lower temperature range may be accomplished by the addition of modifying elements, when this is acceptable to the user.

Plate material, because of its fibrous structure, will show much higher values under notched-bar testing at room temperature than weld metal because the latter, although only partially ferritic, is composed of large columnar grains, which are only partially refined by heat treatment. Figure 14 shows a hardness survey of unannealed welds in 15.56% chromium plate and Table 6 contains test data on a weld of this analysis following heat treatment.

20 to 30% Chromium Steels

Steels having 20 to 30% chromium are non-hardening, notch sensitive and are single-phase ferritic steels which cannot be refined by heat treatment. In multiple-pass welds the heat of welding does not refine underlying layers of weld metal and causes grain growth with an increase in notch sensitivity in the heat-affected zone. Austenitic filler metal is recommended for

Table 5—Test Data on Annealed 12–14% Chromium Weld and Plate

	Analysis			Mechanical Properties				
	Thickness, In	Cr	C	Tensile Strength, Psi.	Yield Point, Psi.	Elongation in 2 In., %	Reduction in Area, %	Bend Elongation, %
Weld	5/8	12.2	0.08	77,500	54,200	30	65	72
Plate	5/8	12.4	0.08	74,500	42,000	37	71	

NOTE: Charpy keyhole notch impact value for weld metal, 20 to 30 ft.-lb.

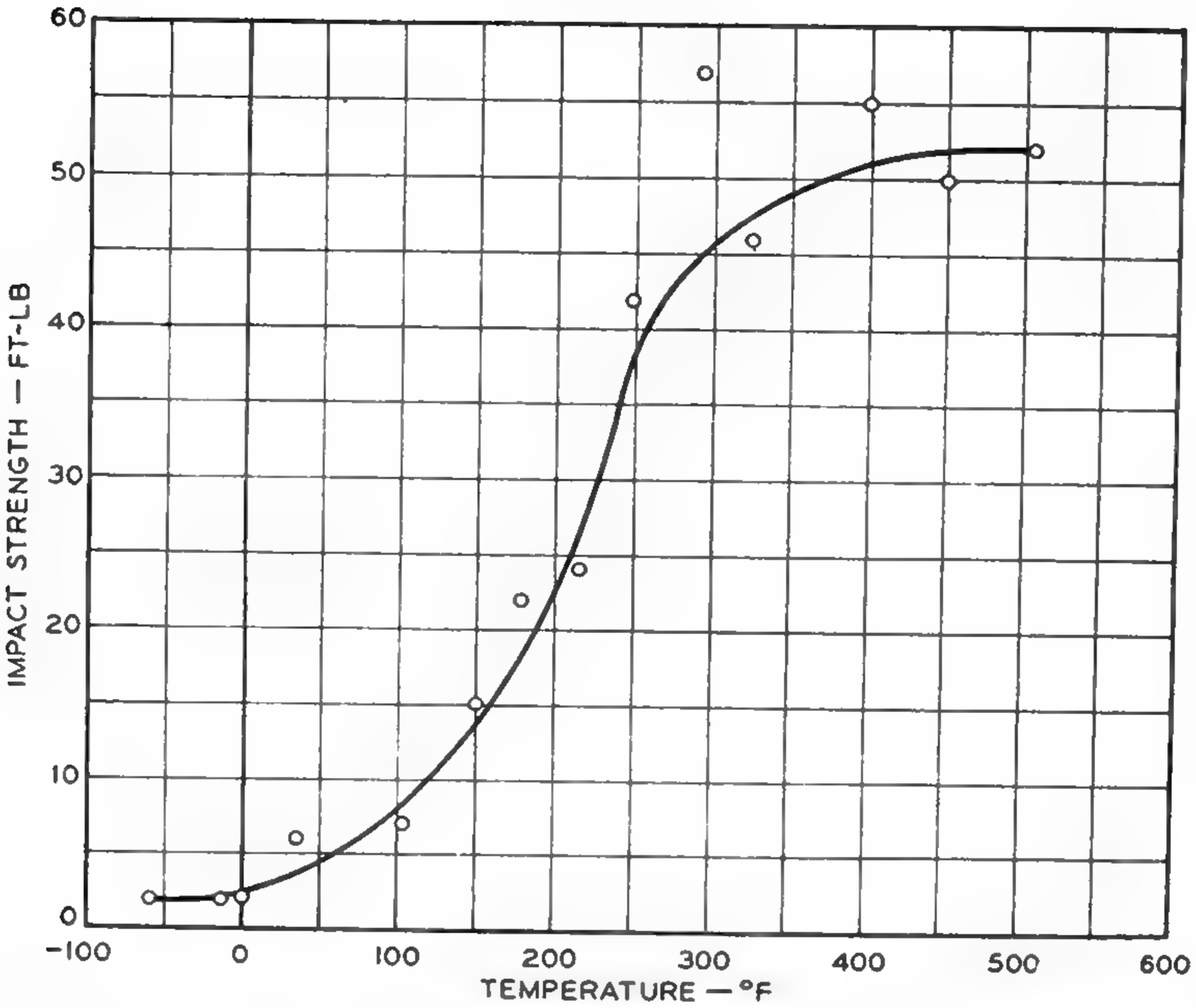

Fig. 13.—Effect of Temperature on Notched-Bar Impact Strength of 16% Cr Weld Metal

Charpy specimen with Izod vee notch.

welding steels in this range since the straight chromium deposits are too brittle to carry appreciable stress. The effect of rolling when producing plate material is to break down the coarse dendritic grains of the ingot and produce a fibrous structure with favorable directional properties. An increase in notch sensitivity takes place in the heat-affected zone of weldments as a result of recrystallization and grain growth. The addition of nitrogen in amounts up to 0.25% is effective in improving the structure somewhat but the notch sensitivity of welds is only slightly improved as can be seen from Fig. 15. Nitrogen is apparently more effective for improving the properties of wrought material (see Table 7), and the addition of nitrogen has become general practice in steel making. Figure 16 illustrates the low hardening characteristics of a 26.7% chromium steel.

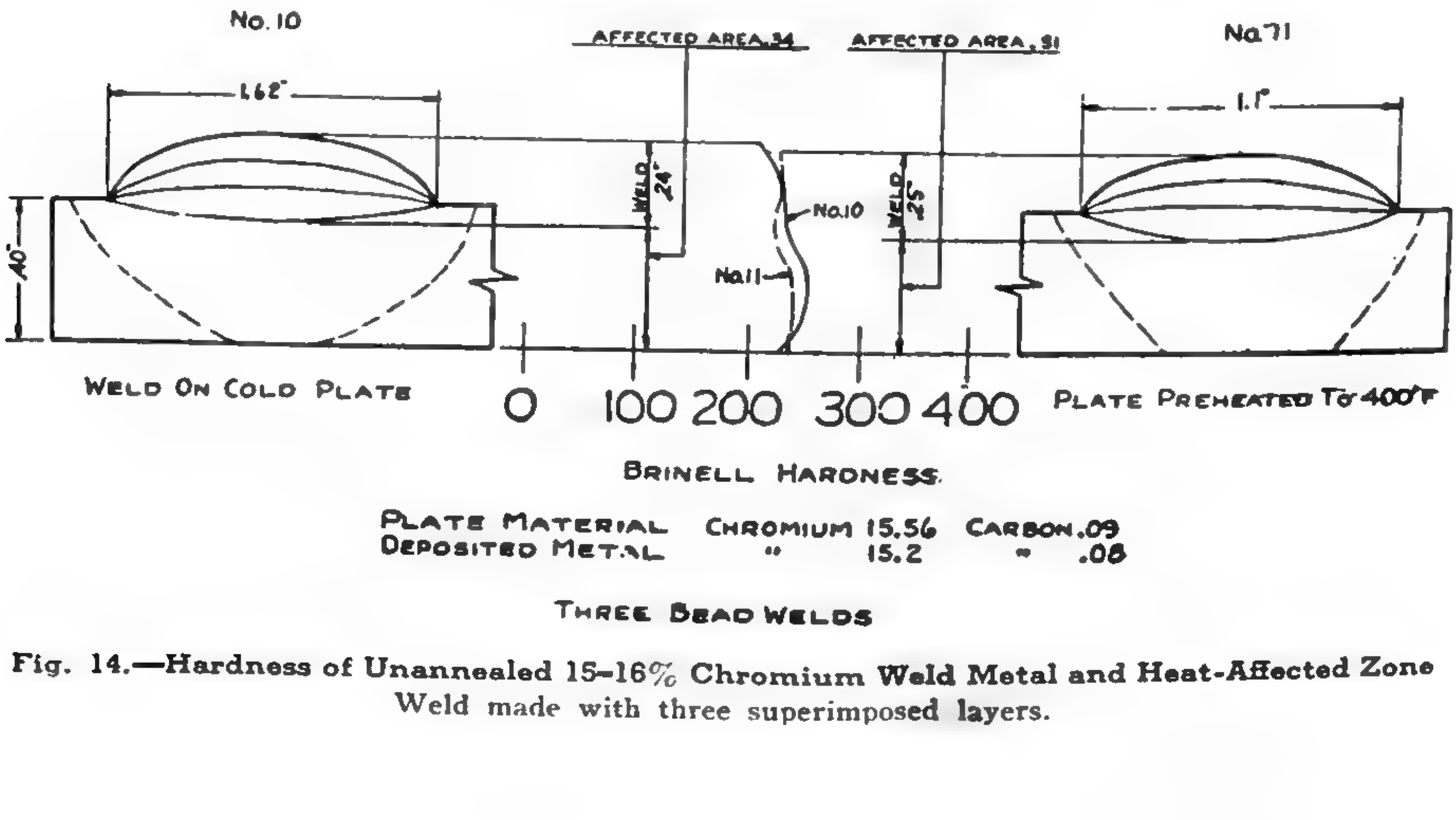

Fig. 14.—Hardness of Unannealed 15–16% Chromium Weld Metal and Heat-Affected Zone

Weld made with three superimposed layers.

Because of their poor mechanical properties, particularly in the heat-affected zone of weldments, the use of steels within this chromium range has been rather limited. By adding from 3 to 5% nickel the toughness of these steels is improved and this modified grade which is partially martensitic, has probably been more widely used than the steels without modification. An austenitic filler metal is also recommended for this modified steel although filler metal having a composition duplicating that of the base metal has better properties than the unmodified weld metal.

Shielded Metal Arc Welding

Commercial covered electrodes are available for welding all of the chromium steels. Welding electrodes containing over 11% chromium have arcing characteristics quite similar to other stainless electrodes including the austenitic types and some electrode manufacturers use the same basic covering for all electrodes containing over 3% chromium. Electrode coatings are not standardized but two types in general use are the so-called *lime* and the *lime-titania* coverings.

Table 6—Test Data on Annealed 15–16% Chromium Weld and Plate

	Thickness, In	Analysis, Cr	Analysis, C	Mechanical Properties: Tensile Strength, Psi.	Yield Point, Psi.	Elongation, in 2 In., %	Reduction in Area, %	Bend Elongation, %
Weld	3/4	15.64	0.08	77,000	61,250	32	48	55
Plate	3/4	15.75	0.04	70,200	42,500	42	60	..

NOTE Charpy keyhole notch impact value for weld metal, 12 to 25 ft.-lb.

Several particular welding difficulties seem to be inherent with straight chromium weld deposits and should be anticipated. Internal porosity is often difficult to eliminate, particularly when welding in any position other than downhand. The electrode which deposits a perfectly sound weld in the flat position will often produce unacceptable porosity in the vertical and overhead positions. The slagging characteristics of these electrodes are not as favorable for vertical and overhead welding as they are in many carbon steel electrodes, and this may contribute to the entrapment of porosity. Another factor may be the lower fluidity of the chromium steel weld deposits as compared with carbon steel weld metal. Heating the electrode to about 500°F. just prior to welding has proved effective for reducing the porosity

Chromium has a strong influence on the thermal conductivity of steel, the conductivity decreasing rapidly with increasing chromium content, up to 20% chromium (see Fig. 11). Lowering the thermal conductivity is beneficial for obtaining complete fusion when welding thick material, but it can result in great difficulty with porosity when welding thin material because of the tendency for the pool of molten metal to overheat. This is true with any welding process involving an electric arc between the electrode and the work.

When welding these steels with austenitic electrodes, the deposit should be sufficiently high in nickel and chromium to allow for dilution which results from mixing with base metal. E310 electrodes (25% chromium, 20% nickel) have been used extensively for welding all grades of chromium steels although no dilution in chromium results from welding the highest chromium steels. Some loss in chromium occurs in the arc as a result of oxidation and this must be compensated for in the analysis of the core wire; the loss in nickel is negligible. Wide variations in arc length should be avoided, but most electrodes are not sensitive to moderate changes in this variable. In order to prevent carbon pickup in the deposited metal, materials containing carbon are seldom used in coverings of electrodes for these alloys. Adjustments in analysis are frequently made by additions of alloying elements to the covering. This is a convenient method for adding molybdenum and other modifying elements to produce different grade electrodes with the same core wire.

Atomic Hydrogen Welding

Atomic hydrogen welding is used for all types and grades of chromium steel with excellent results. The welds have

good mechanical properties and corrosion resistance and the shielding afforded by the hydrogen atmosphere is complete enough so that a flux is not required. Where filler metal is required, bare rods of a straight chromium analysis similar to that of the base metal or a suitable austenitic grade may be used without flux.

ing the ferritic steels. See Chapter 11 for further information on atomic hydrogen welding.

Inert-Gas Metal-Arc Welding

Either helium or argon may be used for welding any of the chromium steels. Either d.c., straight polarity or a.c. may

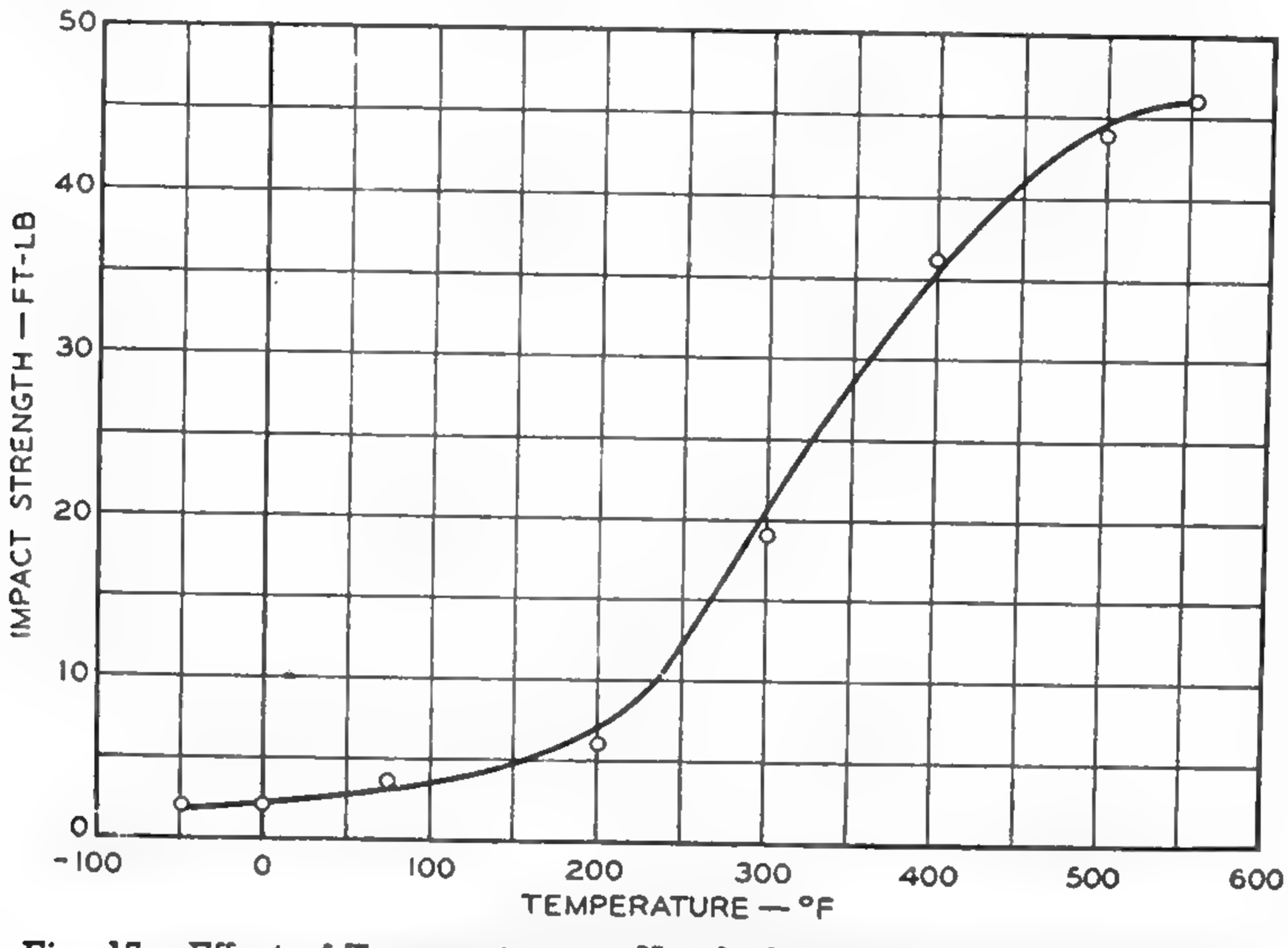

Fig. 15.—Effect of Temperature on Notched-Bar Impact Strength of 27% Cr Weld Metal Modified with 0.22% Ni
Charpy specimen with Izod vee notch.

The choice of filler metal analysis depends on the same factors which govern the type of filler metal used with other processes. This process has special advantages for welding edge and corner joints in light gage sheet. A common use is for seal welding light-walled tubes to tube sheets. For such an application it has the advantages of oxy-acetylene welding as regards close control of the fusion rate without its disadvantages of carbon pickup, excessive oxidation and a low flame temperature. The very high temperature of the atomic hydrogen arc gives the welder a wide latitude in exercising control over the distance of the arc from the work. The heat from the hydrogen arc can be used to advantage as a means of providing part or all of the preheat required, but overheating of light gage sheet must be guarded against to avoid troublesome distortion. Overheating can result in grain growth with accompanying embrittlement over a relatively wide heat-affected zone when weld-

be satisfactorily used with either gas. Exclusion of tungsten from the weld metal is difficult to prevent completely, although it may be minimized by using currents within the range recommended for the size of electrode being used. When tungsten is transferred in the form of globules or particles, it shows up as white specks in X-ray radiographs.

This process has been found suitable for many applications where atomic hydrogen welding has previously been used, because of the greater welding speeds possible. It is displacing the atomic hydrogen process in certain applications for welding thin materials where distortion must be held to a minimum. It is being widely used for seal welding tubes to tube sheets and for similar applications. When filler metal is required, a bare welding rod is used, the composition depending on the same factors as previously discussed. When welding butt joints without the addition of filler metal, the edges to be joined should have no bevel

or groove and should be brought together with no root opening. A tightly-fitting copper backing should be used to hold the weld depression on the outside to a minimum, but some depression should be expected with the best possible backing.

For information on the general principles involved and equipment required, see Chapter 12.

Submerged Arc Welding

All of the chromium steels may be welded by submerged arc welding, using either the single-pass, double-pass or multiple-pass methods. Either a straight chromium or austenitic electrode can be used. The granular material (flux) used should be in accordance with recommendations of the manufacturer. Reference should be made to Chapter 13 for general information on this process and equipment required. Because of the high heat input when depositing heavy layers, preheating may or may not be required depending upon the geometry of the weldment, but less preheat is generally required for the same joint than with other processes. Only an austenitic electrode should be used for welding steels having above 16% chromium with this process, since the excessively large columnar grains of the heavy layer straight chromium deposits are particularly notch sensitive and generally have very poor mechanical properties. Heavy layer deposits in any of the ferritic steels result in comparatively wide heat-affected zones embrittled by grain growth, and for this reason submerged arc welding has been used very little for welding steels with more than 16% chromium.

The hardened heat-affected zones produced in the martensitic and bainitic steels by this process are wider in proportion to the heat input than with other arc-welding processes which involve lighter layers and the hardness is no less than that of the more narrow hardened zones for reasons which have been explained. Heavy layer weld deposits in the hardenable steels are sensitive to incipient cracks formed as a result of segregation of impurities during solidification. Therefore, all important stress-carrying welds, such as the main seams of pressure vessels, should be radiographed. Irregularities in the arc at starting points and at interruptions often act as notches for promoting cracks and high preheating temperatures are sometimes required to avoid serious difficulties from this source.

When an austenitic electrode is used for single- or double-pass welding, the wire analysis must leave ample margin for dilution of the weld by the base metal. The weld metal may be composed of up to 40% or more of fused base metal, depending on the groove shape used and other welding variables. Sufficient procedure tests and deposited metal analyses should be made to make certain that the final weld analysis is completely austenitic under all conditions that will be met in service. Providing surplus nickel in the electrode is the most common method employed for assuring a completely austenitic structure. The granular material which completely smothers the arc in this process provides protection against oxidation by the air, and loss of those elements such as chromium which are easily oxidized is very small.

Table 7—Effect of Nitrogen on Mechanical Properties of 22.4% Chromium, 0.10% Carbon Steel

Mechanical Property	Nitrogen, % 0.032	Nitrogen, % 0.21
Tensile strength, psi	77,600	85,000
Yield strength, psi	46,500	54,000
Elongation in 2 in., %	30	29
Reduction of area, %	60	66
Izod impact, ft.-lb.	4	24
Brinell hardness	149	166

NOTE: Heat treatment—water quench from 1650°F. after soaking 6 hr.

Spot Welding

The low thermal conductivity of the higher chromium steels is favorable for spot welding (Fig. 11), but the air-hardening properties of the steels having up to 14% chromium and the notch sensitivity after grain growth of the ferritic steels are decidedly disadvantageous to spot welding. However, carbon steel pressure vessels having spot welded linings of 11 to 14% chromium steels have been in oil refining service for many years and have been very satisfactory. Probably the safest procedure for spot welding the hardenable alloys is to preheat before welding and to use a schedule which includes a tempering treatment (see Chapter 16). Furnace stress relieving of weldments involving spot welds in the air-hardening steels should be mandatory and

this requirement is included in many specifications. There has been little demand for the use of spot welding in fabricating the ferritic steels, and because the properties of the heat-affected zone in these materials cannot be restored by heat treatment, spot welding is not recommended if reliance must be placed on either the soundness of the spot welds or their capacity to withstand working stresses.

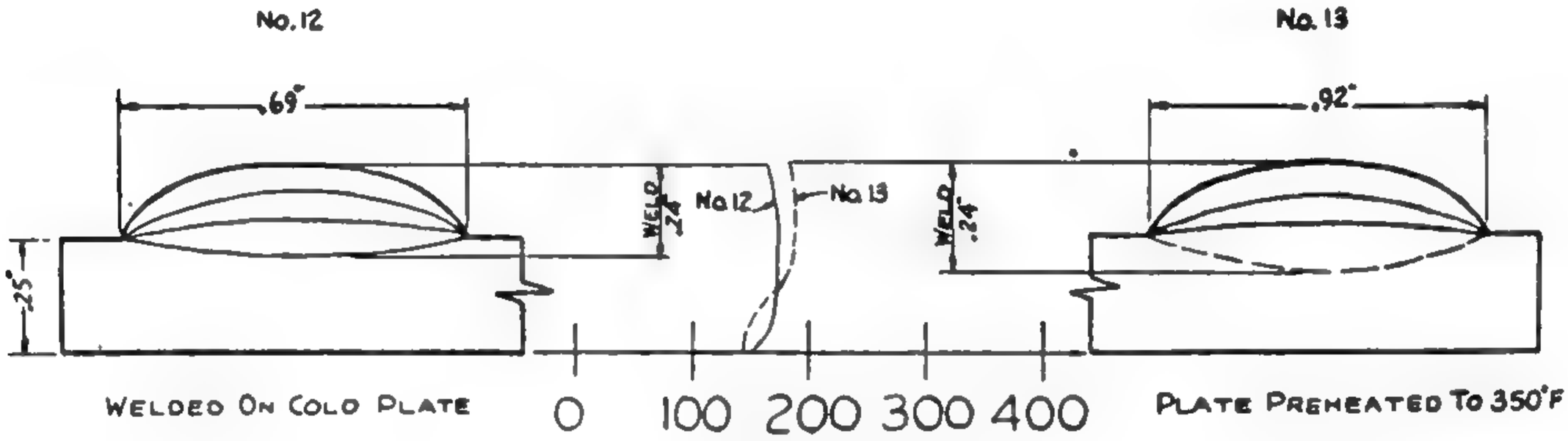

Fig. 16.—Hardness of Unannealed 23–30% Chromium Weld Metal and Heat-Affected Zone
Weld made with three superimposed layers.

The so-called non-hardening grade, 11 to 14% chromium, containing aluminum (AISI Type 405), has been used to a considerable extent for spot-welded construction, and because of its low propensity for hardening should be considered when a steel having a chromium content within this range is required. Recommended spot welding practices, applicable specifically to the chromium steels, have not been adopted, but as a guide reference may be made to the practices recommended for spot welding hardenable low-alloy steels and stainless steels included in *Recommended Practices for Resistance Welding*, published by the AMERICAN WELDING SOCIETY (see Chapter 16). The practices recommended for steels of highest hardenability should closely approximate good practice for welding the 3 to 11% chromium steels and the practice recommended for welding stainless steels should compare closely with acceptable practice for the steels having over 11% chromium.

Seam Welding

Seam welding, which is fundamentally a series of overlapping spot welds, can be used for all of the chromium steels with the same limitations given above for spot welding. Whereas spot welding or seam welding a chromium steel to itself usually involves a joint between two relatively light sheets, welding linings to carbon steel vessels presents quite a different problem since it involves a weld between a light sheet and a much heavier plate having greater mass for conducting heat away. Higher currents, greater pressures and larger welds must be used for welding the linings than are employed for welding two sheets of equal or nearly equal thickness, resulting in deeper surface indentations at the spot or seam welds. Porous welds often result from attempting to spot or seam weld the steels with up to 11% chromium without first removing all mill scale by sandblasting or pickling. The light scale formed on the higher chromium steels has not proved detrimental to welding but pickling of these steels is customary for surface inspection. The fused metal has a composite analysis which will vary, the actual analysis depending on a number of variables.

Seam welding has been used to some extent for joining light linings to heavier plate, but the equivalent, consisting of overlapping spot welds, has been used extensively. Seam welding light sheets of chromium steel to sheets of the same analysis is a comparatively simple operation since many conditions are favorable, including low heat conductivity, little re-

straint to deformation stresses and no mixing of dissimilar metals in the fusion zone. There are no written rules which if followed verbatim will guarantee good seam welding. The procedures for welding each combination of materials should be established by preliminary tests involving the same geometry as nearly as possible as that which will be used on the production job.

Flash Welding

Flash welding is extensively used for joining chromium steel tubes having from 3 to 10% chromium. To a lesser extent it has been used for welding tubes and pipe having from 10 to 16% chromium. Superheaters for power boilers often involve tubing of several different grades of chromium steel and they are often joined to each other by flash welding. The techniques follow standard flash welding practice with the exception that to permit removing the flash from the inside of the weld softening by heat treatment is required for the air-hardening steels. The addition of titanium to the low chromium grades has proved effective for reducing the total heat treatment time required to produce the necessary softening effect. Since each joint is usually given a local heat treatment, the total saving in time is considerable where a number of joints are involved. For best results a comparatively long burnoff and a heavy upset are recommended for these materials. No difficulty is experienced in flash welding any of the steels having up to 16% chromium to themselves, to another chromium steel, to carbon molybdenum steel or to plain carbon steel. Although the ferritic chromium steels have not been flash welded too often, they can be welded successfully by this process if the loss in properties which always accompanies the heating of these materials can be tolerated. The introduction of an inert or non-oxidizing atmosphere around the weld during the flashing period has proved to be effective for reducing the formation of chromium oxide and improving the mechanical properties of the welds when flash welding any of the chromium steels. Poor properties of welds which are not protected in this manner may be attributed to entrapment of oxide in the joint, which is very difficult to expel because of the highly refractory nature of chromium oxide

WELDING CHROMIUM STEELS TO OTHER STEELS

General

All types and grades of the chromium steels are successfully welded to each other, to carbon steel, to the austenitic steels and to other alloy steels. The most economical utilization of these materials often calls for the combination of several types of the chromium steels and other steels in a single weldment. For example, in steam superheaters materials may be included which involve welded joints as follows: carbon steel to carbon-molybdenum steel, carbon-molybdenum steel to $1^1/_4$% chromium–$1^1/_2$% molybdenum steel, the latter to 5% chromium–$^1/_2$% molybdenum steel, and the latter to an austenitic steel. In steam piping, one of the lower chromium steels frequently is welded to an austenitic steel. Outside attachments to pressure parts such as brackets and hanger lugs are frequently made of carbon steel to reduce cost. Steam jackets of chromium steel pressure vessels usually are made of carbon steel, and, therefore, welded joints between the alloy vessel and the jacket are involved.

In every case where any one of the chromium steels is welded with an austenitic filler metal, and there are large numbers of such joints in service, a fusion line between the chromium steel and the austenitic weld metal is involved. In a joint between two dissimilar metals the metallurgy of both base metals and the weld metal must be taken into consideration when establishing welding procedures and heat treatments. Since the weld metal is a composite of the filler metal deposited and the fused base metals, three dissimilar metals are actually involved in these joints. The proportion of deposited metal and the two dissimilar fused base metals in the weld metal is dependent upon several variables including the plate thickness, welding process used, size electrode, welding current, shape of groove, etc.

The choice of electrode or welding rod composition for the great majority of joint combinations is simplified by following several general rules.

1. An austenitic filler metal should be used for welding any one of the chromium steels to an austenitic steel.

2. For welding a hardenable chromium steel to another with a higher chromium content, a filler metal having chromium equal to that in either the lower chromium or the higher chromium steel may be used. Furthermore, a filler metal with chromium of any amount between these limits is just as satisfactory if the weldment is properly heat treated after welding.

3. A general rule for welding any chromium steel to any low-alloy steel is to use a filler metal (*a*) having the same composition as the low-alloy steel provided that the alloying elements it contains are essential for the service application, and (*b*) having any low alloy composition that will provide the mechanical properties required for the service application. With any low-alloy filler metal it is, of course, necessary to consider the chromium that will be picked up from the fused chromium steel base metal.

4. For welding any chromium steel to a carbon steel, carbon steel filler metal can be used. Although a chromium steel filler metal can also be used, it is preferable in every case to use filler metal which is least hardenable and this filler metal is usually the least expensive.

5. An austenitic filler metal can be used for welding one chromium steel to another or to any other steel by observing the general rules given above for using such filler metal in welding all types of chromium steels.

In determining the proper heat treatment for a weld which joins a chromium steel to any other steel, it is inadvisable to apply general rules and the advice of a competent metallurgist should be sought. Because of the infinite number of material combinations possible, recommended heat treatments for joints involving dissimilar metals are not included in this chapter. In a very limited way, however, a general rule may be applied for the heat treatment of such welded joints where the mechanical properties are the only concern. In such cases, a heat treatment which will soften the heat-affected zones of both base metals is usually suitable for the weld metal also, provided its composition conforms to the recommendations previously given. Furthermore, in most cases, the heat treatment necessary for softening the material which requires the highest temperature and/or longest soaking time, is usually suitable for the other materials involved, provided their loss in tensile strength is acceptable.

Authorities agree that the chromium steels can be welded to any of the other alloy steels if the right procedures are used and the joints will have satisfactory properties for operation at temperatures up to about 800°F. However, it is yet to be established whether or not the differences in coefficients of thermal expansion of the chromium steels and the austenitic steels impose any limitations as regards material thickness to electrode diameter ratio, and cyclic temperature operation on welds joining these materials.

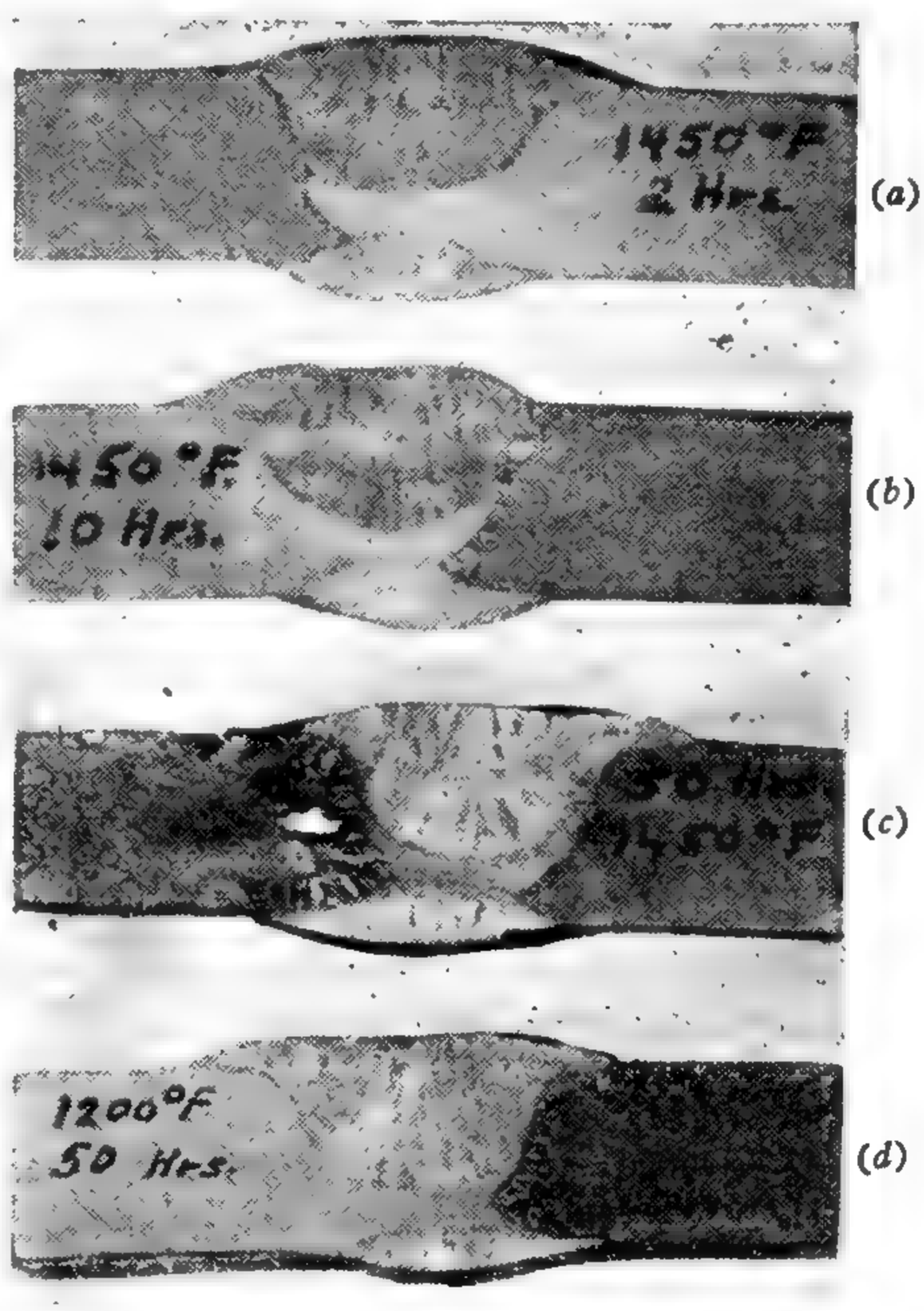

Fig. 17.—Macrographs of Weld Between Carbon Steel and 17.5% Chromium Steel Using 16% Chromium Weld Metal Showing Carbon Migration

There is a difference of opinion among authorities over the significance which should be attached to carbon migration which takes place at temperatures over 800°F. adjacent to the fusion line where any two materials having greatly different chromium contents are joined. Migration is accelerated by an increase in temperature and the degree of decarburization which results is a function of time. Chromium has a high affinity for carbon and when one steel containing chromium is welded to another which contains much

less or none of this element, carbon is drawn from the low chromium material toward the high chromium material. If carbon migration is extensive it will be indicated by a decarburized zone in the carbon or low-chromium steel and by a dark line at the fusion zone, whether the high-chromium steel is a chromium-nickel austenitic steel or a straight chromium steel. Carbon migrates very slowly at temperatures between 800 and 1000°F., but relatively rapidly at temperatures above 1100°F. Annealing or normalizing materials or welds in which migration has taken place will eliminate the high carbon zone at the fusion line by returning this carbon into solution and will restore carbon to the depleted zone. Figure 17 shows a macroscopic study of a joint in which extensive migration has occurred as a result of holding at high temperatures for long periods. The loss in joint properties, if any, as a result of ordinary stress relief and annealing treatments is not apparent when making standard mechanical tests. Rotating beam fatigue tests have been conducted on welded joints involving an austenitic weld in carbon steel and these tests applied to both unnotched and notched specimens (see Fig. 18) have failed to indicate any one zone especially susceptible to failure. Figure 19 shows a typical path of failure through the decarburized zone, and Fig. 20 the path of a failure through the austenitic weld. The welds were treated at 1200°F. for 15 hr. in order to produce extensive migration for these tests.

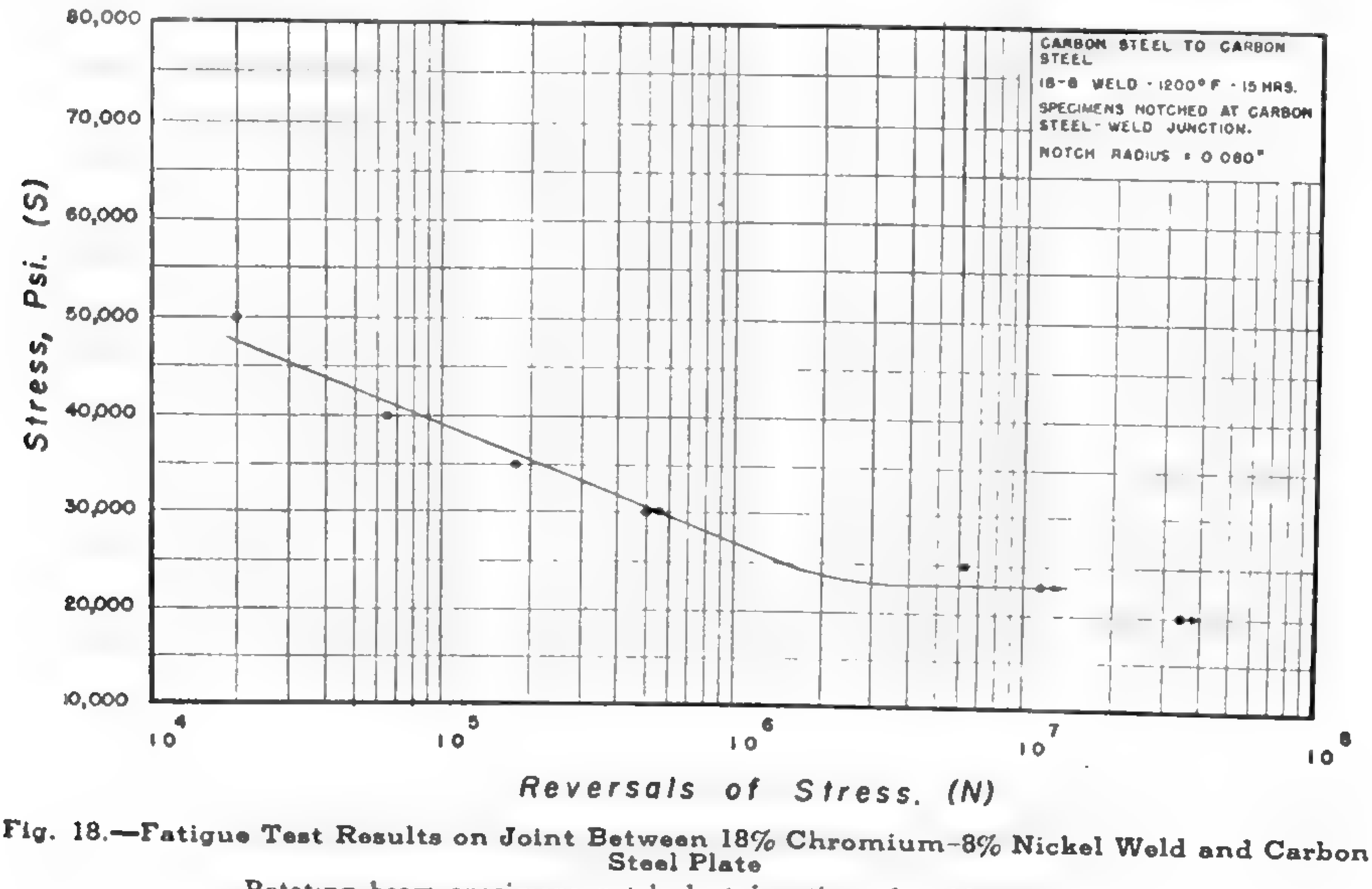

Fig. 18.—Fatigue Test Results on Joint Between 18% Chromium–8% Nickel Weld and Carbon Steel Plate

Rotating beam specimens notched at junction of weld and plate.

HEAT TREATMENT

General

Applications requiring the use of expensive materials such as the chromium steels usually will justify the added expense of heat treatment in order to develop optimum properties in the welded joints. Probably no other widely used materials are as greatly benefited (through improvement in mechanical properties of the joints) by heat treatment. Heat treatment of these steels is used primarily for reducing hardness, increasing ductility, reducing notch sensitivity and for stress relieving. It may also be used for grain refinement of forgings and castings of the hardenable steels. However the effect on corrosion resistance is considered only a secondary purpose for heat treatment for all the chromium steels except those containing 14 to 18% chromium.

50 ×

Fig. 19.—Typical Path of Failure Through Decarburized Zone in Carbon Steel Plate Adjacent to Weld-Plate Junction of Notched Fatigue Specimen

(*a*) Failure path.
(*b*) Decarburized zone in plate.
(*c*) Weld-plate junction.
(*d*) Notch profile.
(*e*) Weld.

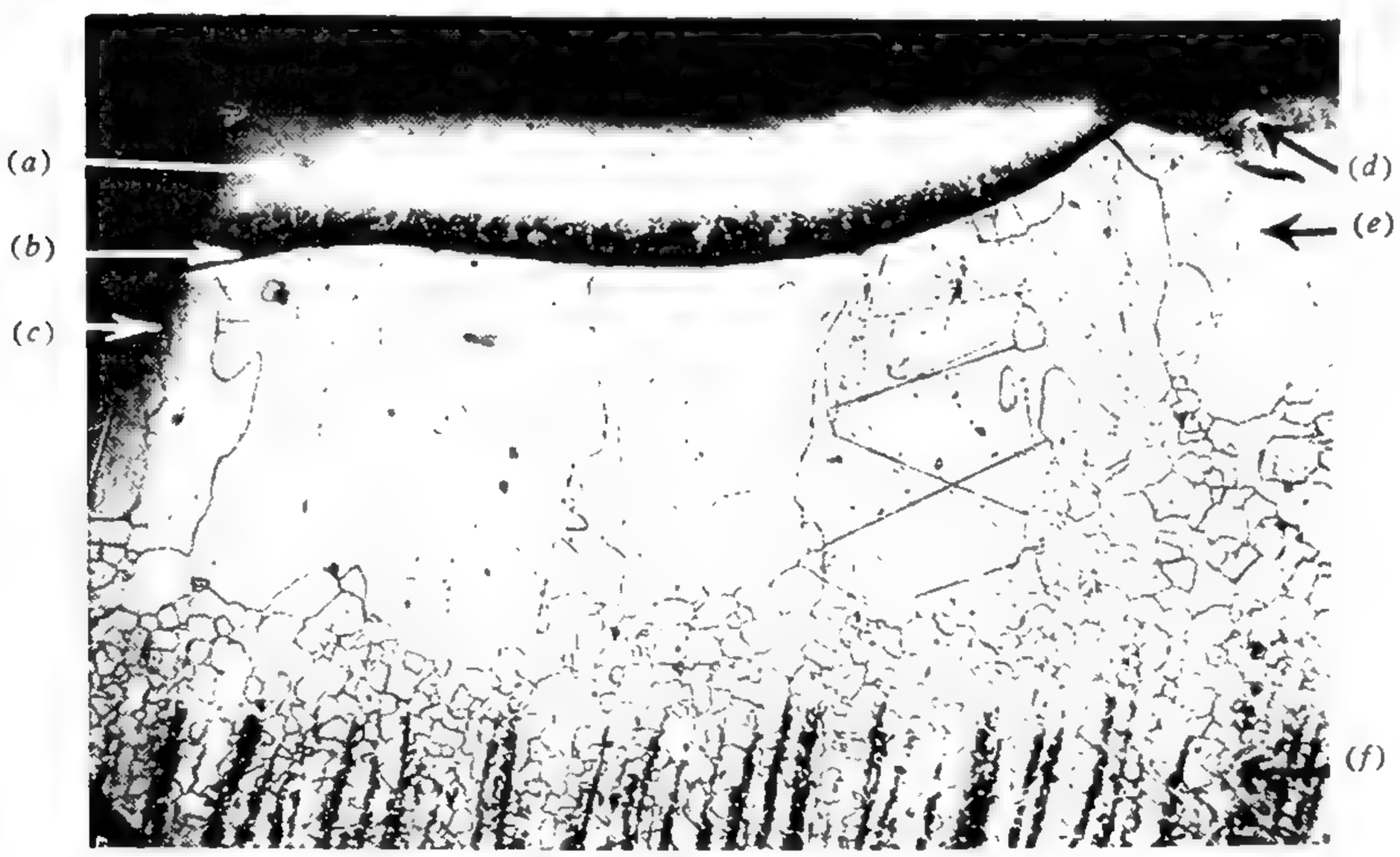

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Fig. 20.—Typical Path of Failure Through 18% Cr–8% Nickel Weld of Notched Fatigue Specimen

(See Fig. 18)

(*a*) Weld.
(*b*) Weld-plate junction.
(*c*) Notch profile.
(*d*) Failure path.
(*e*) Decarburized zone in plate.
(*f*) Normal plate.

3 to 10% Chromium Steels

These steels may be softened after quench hardening either by tempering at a temperature between 1350 and 1400°F. for several hours or by heating to about 1650°F. and cooling very slowly. The isothermal transformation diagram for 5% chromium–0.5% molybdenum steel (Fig. 21) shows that after austenitizing at 1650°F., softening may be greatly accelerated by cooling to about 1350°F. and holding at this temperature for about one hour. The rate of cooling after this treatment does not affect the final hardness and is only restricted in order to minimize cooling stresses which may be induced by differential shrinkage. By referring to the hardness values given in Table 8, the greater efficiency of the latter treatment for reducing hardness in a shorter period of time is readily apparent. Isothermal transformation curves for some of the steels within this group are not available, but they follow very closely the pattern of Fig. 21. A few tests on any particular analysis will serve to locate the knee of the curve accurately enough for establishing a practical heat treatment.

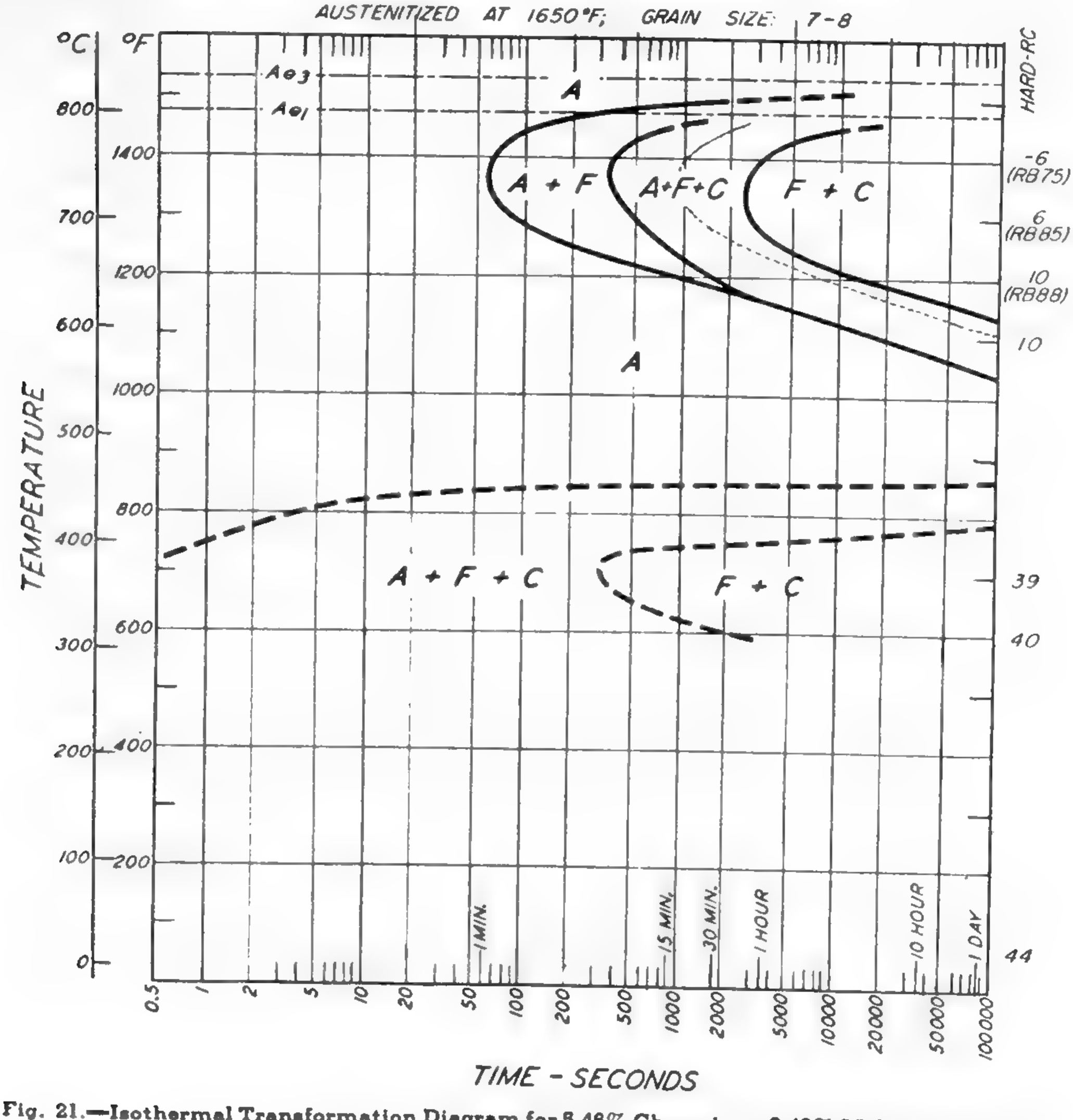
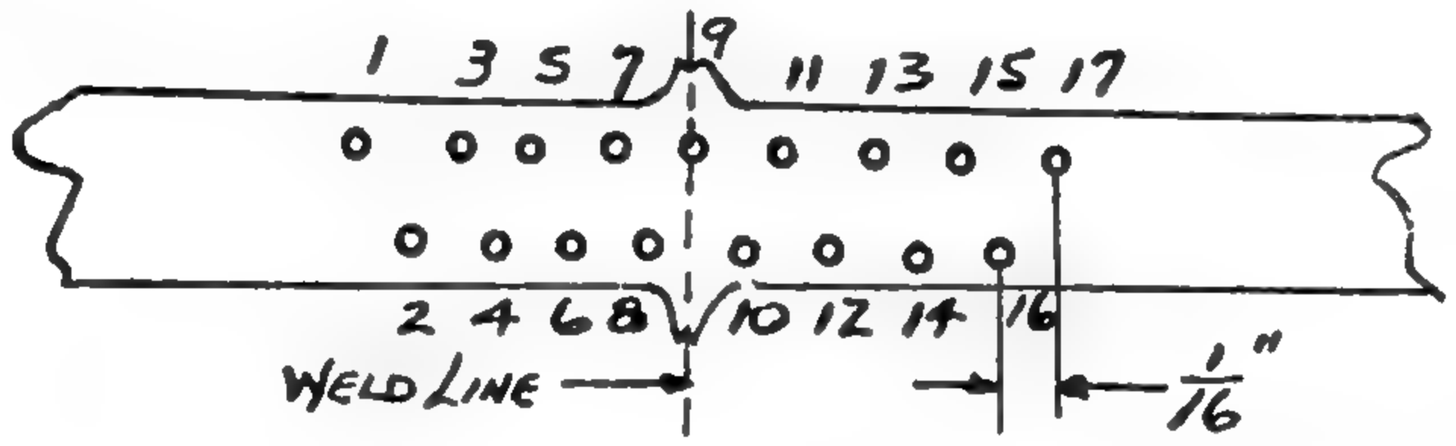


Fig. 21.—Isothermal Transformation Diagram for 5.46% Chromium–0.42% Molybdenum, 0.11% Carbon Steel

11 to 14% Chromium Steels

A tempering treatment for softening and stress relieving low-carbon chromium

Table 8—Hardness Survey of Flash Weld in 4% Chromium Tubing After Various Heat Treatments



Heat Treatment	Rockwell B Hardness at Numbered Locations																	[a]
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
As-welded	76	78	80	81	86	83	91	100	109	105	82	76	76	77	77	77	76	..
Held at 1650°F. for 5 min., furnace cooled to 1375°F. in 19 min., held at 1375°F. for 0 min. and air cooled.	70	69	70	68	70	70	73	75	79	78	77	70	71	70	71	71	71	..
Held at 1650°F. for 5 min., furnace cooled to 1375°F. in 19 min., held at 1375°F. for 5 min. and air cooled.	78	81	80	82	82	77	79	78	79	77	79	79	81	79	81	80	80	..
Held at 1650°F. for 5 min., furnace cooled to 1350°F. in 19 min., held at 1375°F. for 10 min. and air cooled.	76	76	77	78	76	72	75	73	74	71	74	74	77	77	76	77	76	..
Held at 1650°F. for 5 min., furnace cooled to 1375°F. in 19 min., held at 1375°F. for 15 min. and air cooled.	74	71	74	70	73	73	73	71	73	72	72	72	73	74	73	73	71	..
Held at 1650°F. for 20 min., furnace cooled to 1375°F. in 14 min., held at 1375°F. for 15 min. and air cooled.	81	82	82	82	82	83	82	81	77	81	82	83	82	84	82	84	82	77
Held at 1650°F. for 20 min., furnace cooled to 1375°F. in 14 min., held at 1375°F. for 30 min. and air cooled.	72	71	70	71	71	71	72	72	74	73	73	72	71	71	71	71	70	71
Held at 1650°F. for 20 min., furnace cooled to 1375°F. in 14 min., held at 1375°F. for 60 min. and air cooled.	70	72	69	72	71	72	72	74	74	74	72	72	71	72	70	72	68	73
Stress relieved at 1375°F. for 10 min.	71	70	70	70	70	70	70	91	93	93	72	71	71	71	70	71	70	92
Stress relieved at 1375°F. for 30 min.	69	71	70	71	70	71	74	90	93	83	75	70	70	70	70	70	71	90
Stress relieved at 1375°F. for 60 min.	72	72	71	72	72	72	73	87	91	87	73	73	73	72	72	72	72	88
Stress relieved at 1375°F. for 120 min.	69	72	68	72	72	73	73	83	91	86	73	73	73	72	72	73	72	87

[a] ¼ by ¼ by 2-in. tubing samples used. First held at 1650°F. for 20 minutes, and air cooled to 109 Rockwell B hardness; then heat treated as shown and hardness determined.

NOTES: Each value average of four readings. Tubing analysis—Cr 4.35, Mo 0.51, C 0.082, Si 0.27 and Mn 0.32.

steels in this range has been the general practice, and reference to Fig. 22 will show that the temperatures usually employed, from 1250 to 1400°F., are effective for this purpose. The addition of chromium raises the critical temperatures so that an austenitizing treatment requires heating to a higher temperature than for the lower chromium steels and this is often impractical. The soaking time required will vary with the temperature used. Holding for 2 hr. at 1400°F. will have the same effect as 4 hr. at 1300°F. 1450°F. and soaking for a minimum of 4 hr. for thicknesses up to 1 in. with an increase of 1 hr. for each additional inch of thickness is recommended as the heat treatment for these steels. A weldment should be cooled in the furnace down to 1100°F., after which it should be removed from the furnace and air cooled. Figure 23 shows the effect of tempering on an intermediate steel of this range. Rapid cooling from 1100°F. is used to avoid temper brittleness (see Fig. 24) and to provide maximum corrosion resistance.

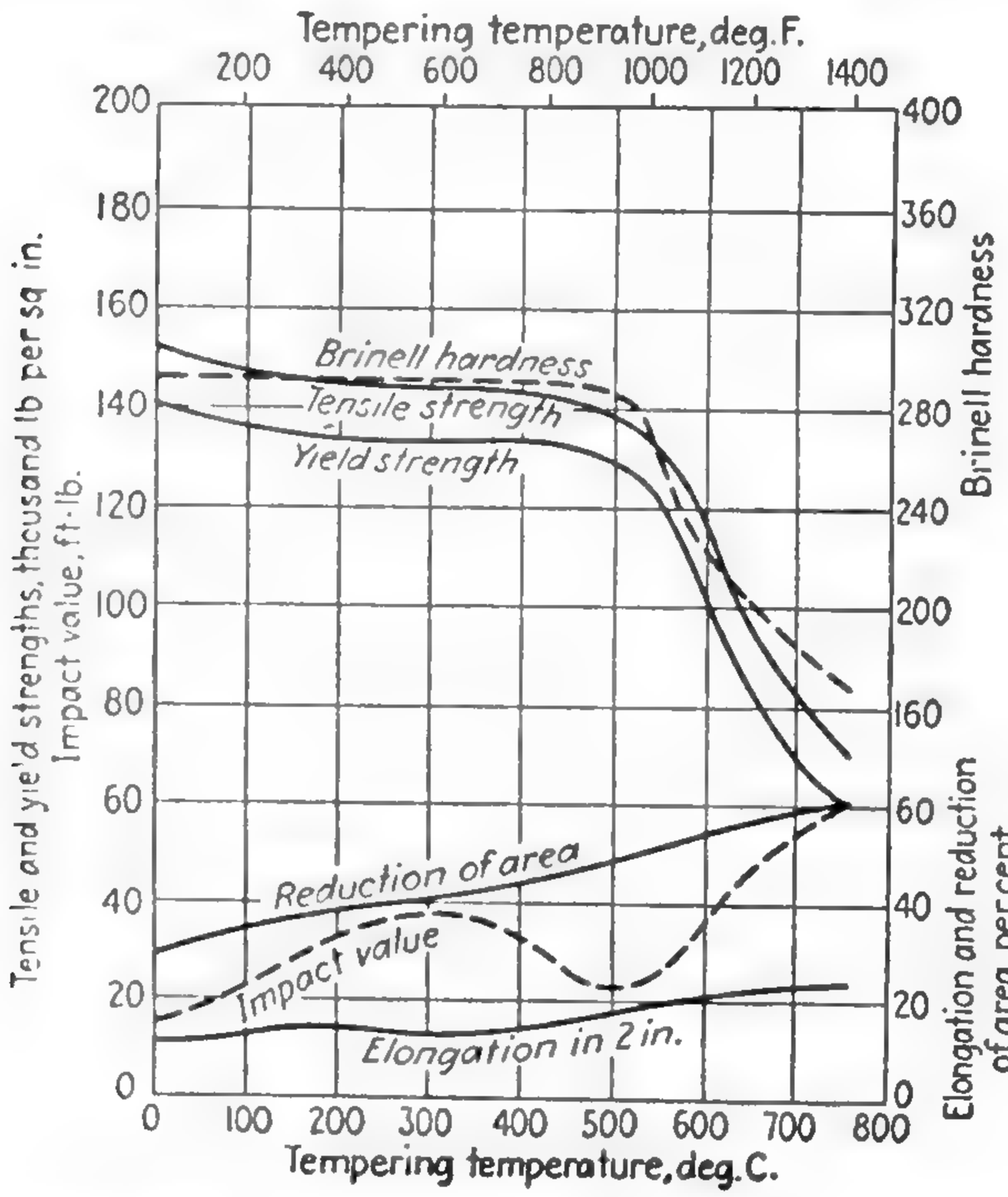


Fig. 22.—Effect of Tempering on a 12.2% Chromium Alloy Quenched from 1850°F.

14 to 18% Chromium Steels

Although this range of chromium covers the transition zone of the chromium steels and a low-carbon steel with 17% chromium will be a single-phase alloy almost completely ferritic whereas a steel with 14.5% chromium will harden perceptibly upon quenching, the heat treatment for any steel falling within these limits is the same. Heating to from 1400 to

20 to 30% Chromium Steels

Rapid quenching following a long soaking period at from 1600 to 1650°F. is necessary for steels in this range in order to develop their maximum toughness and ductility. Soaking periods up to 10 hr. are recommended, although shorter soaking times may be acceptable if the best mechanical properties are not required. Prolonged holding of these ferritic steels

at temperatures from 750 to 1050°F. will cause a deterioration in their properties resulting in marked embrittlement and a loss in corrosion resistance. Reheating to above 1300°F. will quickly remove this brittleness. These alloys while at the embrittling temperature, and in fact at all temperatures above about 250°F., are tough and ductile (see Fig. 15).

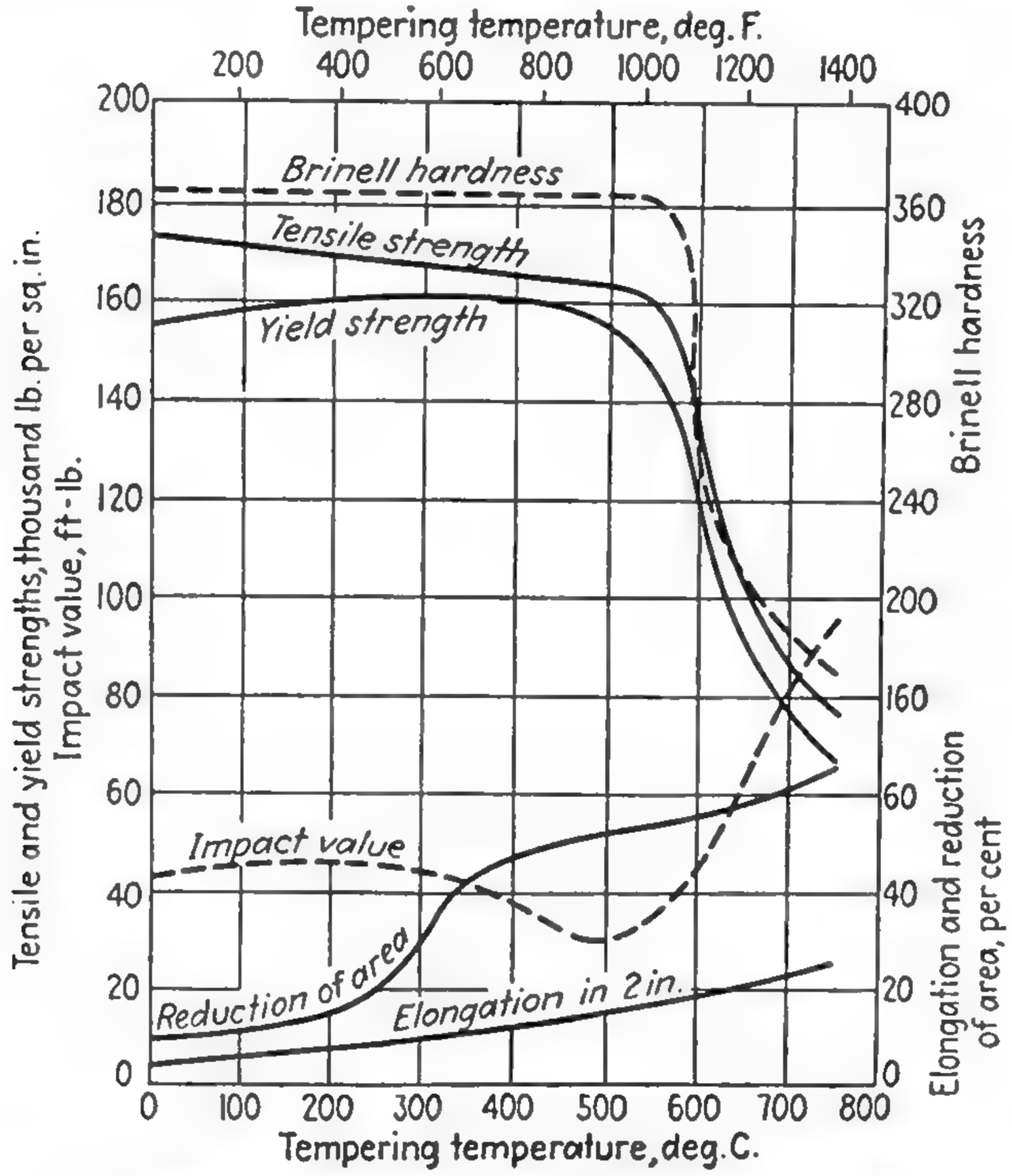


Fig. 23.—Effect of Tempering on a 15.25% Chromium Alloy Quenched from 1850°F.

Dissimilar Steels

The question of heat treating weldments which involve more than one material has been discussed under the heading "Welding Chromium Steels to Other Steels." The heat treatment to use for a given combination will vary since different heat treatments may be necessary for different types of service. The multitude of combinations of chromium steels and other steels which may be welded together makes any attempts to recommend standard heat treatments inadvisable. Competent metallurgical assistance should be sought in determining the best heat treatment for each individual case.

COMMON APPLICATIONS

The common applications for the chromium steels may be summarized as follows:

1. The chromium steels with 3 to 10% chromium have been most widely used in services calling for strength and either oxidation resistance or corrosion resistance at elevated temperatures.

2. The steels having from 10 to 14% chromium have found their greatest use for applications where either oxidation resistance or corrosion resistance is necessary and strength at elevated temperature is of secondary importance.

3. The steels having from 14 to 18% chromium have been largely used for corrosion resistance at relatively low temperatures, having proved particularly serviceable in process equipment for the

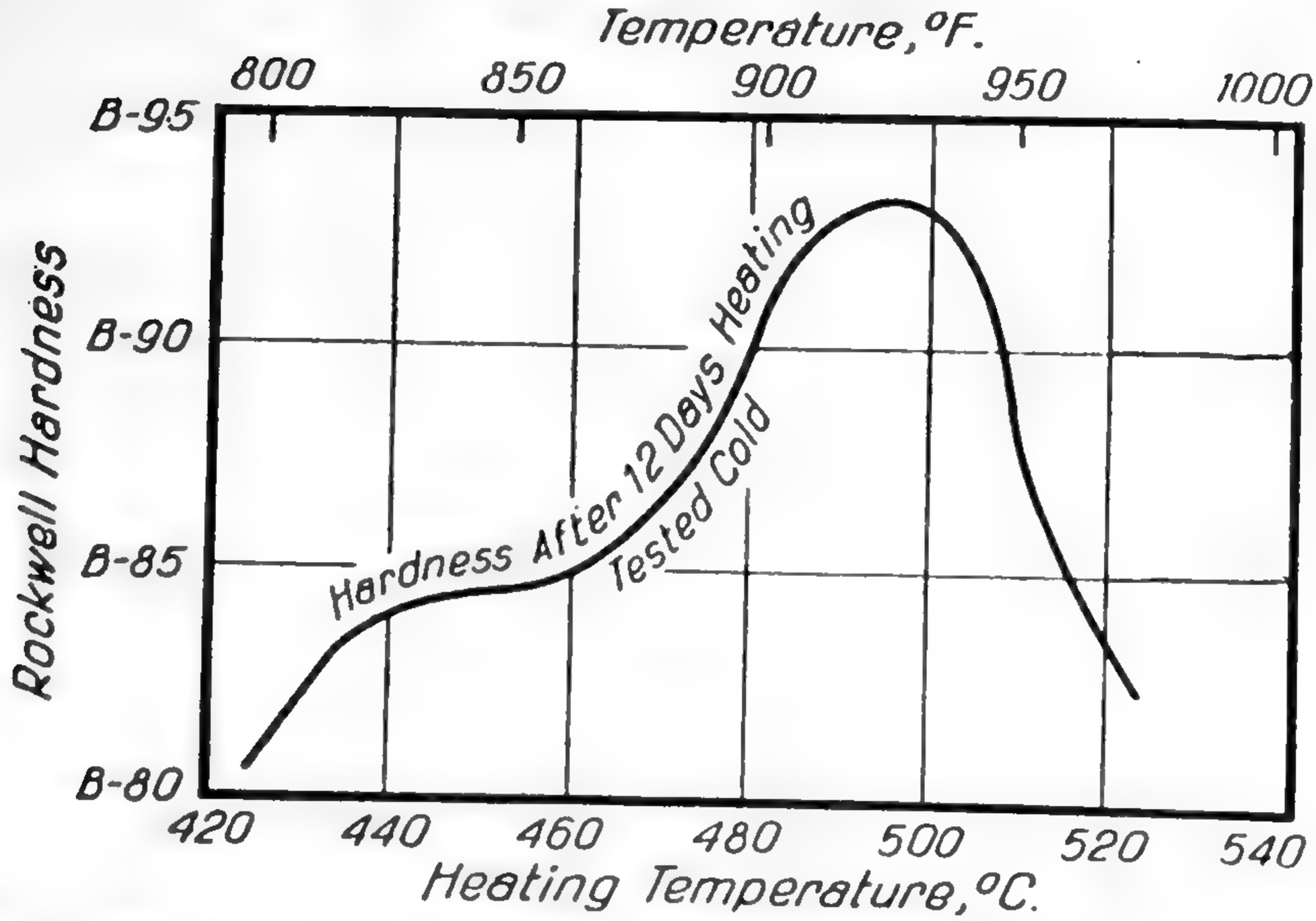


Fig. 24.—Curve Indicating Embrittlement by Increased Hardness of 16 to 18% Cr Iron, Low in Carbon

Pieces were annealed at 1450°F., held at temperatures indicated 12 days, air cooled and hardness measured.

manufacture of nitric acid and in containers for storing and transporting 65% nitric acid.

4. The steels having from 18 to 30% chromium have proved useful primarily for oxidation resistance at very high temperatures but only when their strength and other mechanical properties are unimportant. Steels within this range are ductile and tough while at temperature, but if used above 1800°F., grain growth will cause them to become extremely brittle upon cooling. They are also susceptible to embrittlement as a result of slow cooling after operating at elevated temperatures below 1800°F.

If the importance of the various types of chromium steels is to be judged upon the basis of the amount used or tonnage produced, those types known as the hardenable steels having from 3 to 14% chromium must be considered as of far greater importance than the higher chromium steels. Within the hardenable range those steels with chromium from 3 to 10% can be considered as the most important of the chromium steels since they are probably the most indispensable.

BIBLIOGRAPHY

1. *Chromium-Iron Alloys*, C. E. MacQuigg, Second Edition, The Book of Stainless Steels, American Society for Metals, 1935.

2. *Chromium as an Alloying Element in Steel*, M. A. Grossman, Metals Handbook, American Society for Metals, 1936.

3. *Corrosion Resisting Steels for High Strength*, E. E. Thum, Metal Progress, June 1936.

4. *Influence of Columbium or Titanium additions to 5% Chromium-Molybdenum*, C. L. Clark, Steel, Oil and Gas Journal, April 2 and April 23, 1942.

5. *Atlas of Isothermal Transformation Diagrams*, United States Steel, 1943.

6. *Characteristics and Properties of Some Cast Chromium-Molybdenum Steels*, N. A. Ziegler and W. L. Meinhart, Transactions of the American Society for Metals, 1945.

7. *Properties and Characteristics of 27% Chromium-Iron*, H. D. Newell, Metal Progress, May 1946.

8. *Chromium in Steel*, Walter Crafts, Metals Handbook, 1948.

CHAPTER 31A

AUSTENITIC CHROMIUM-NICKEL STAINLESS STEELS*

GENERAL PROPERTIES

Physical and Mechanical Properties

Classification.—The commercially available wrought austenitic chromium-nickel steels have been classified by the American Iron and Steel Institute as shown in Table 1. A similar list of compositions prepared for stainless steel castings by the Alloy Castings Institute is shown in Table 2.

The nominal physical and mechanical properties of the principal types of wrought austenitic chromium-nickel steels are listed in Table 3. The properties of Type 301 are given for the cold-rolled condition since this grade is commonly welded and used in this condition where it provides a combination of high strength and satisfactory ductility. The mechanical properties of the other grades are given for the annealed condition, in which they are most often used.

Metallurgical Characteristics

Steels of the austenitic chromium-nickel group are characterized by outstanding resistance to corrosion and oxidation. The addition of chromium to steel imparts these characteristics. Chromium, when added alone in the amounts prescribed for this group (16–25%) forms a solid solution in alpha iron. The resultant alloy has a ferritic structure which is strongly magnetic.

The addition of nickel, a strong austenite-forming element, to the above chromium-carbon-iron alloy in the proportions described in this chapter suppresses the magnetic ferritic structure to form a structure completely austenitic at room temperature. The resultant austenitic alloy,

Table 1—AISI Type Numbers and Compositions of Wrought Austenitic Chromium-Nickel Stainless Steels

Type No.	Carbon, %	Chromium, %	Nickel, %	Other Elements, %[a]
301	Over 0.08–0.20	16.00–18.00	6.00– 8.00	.....
302	Over 0.08–0.20	17.00–19.00	8.00–10.00	.....
302B	Over 0.08–0.20	17.00–19.00	8.00–10.00	Si 2.00–3.00
303	0.15 max.	17.00–19.00	8.00–10.00	P, S, Se 0.07 min.; Zr, Mo 0.60 max.
304	0.08 max.	18.00–20.00	8.00–11.00	.....
305	0.12 max.	17.00–19.00	10.00–13.00	.....
308	0.08 max.	19.00–21.00	10.00–12.00	.....
309	0.20 max.	22.00–24.00	12.00–15.00	.....
310	0.25 max.	24.00–26.00	19.00–22.00	Si 1.50 max.
314	0.25 max.	23.00–26.00	19.00–22.00	Si 1.50–3.00
316	0.10 max.	16.00–18.00	10.00–14.00	Mo 2.00–3.00
317	0.10 max.	18.00–20.00	11.00–14.00	Mo 3.00–4.00
321	0.08 max.	17.00–19.00	8.00–11.00	Ti 5 x C min.
347	0.08 max.	17.00–19.00	9.00–12.00	Cb 10 x C min.

[a] Manganese, 2.00 max.; silicon, 1.00 max.; phosphorus, 0.04 max.; and sulfur, 0.03 max., unless otherwise noted.

* Prepared by a committee consisting of F. K. Bloom, Armco Steel Corp., *Chairman;* R. H. Aborn, U.S. Steel Corp.; J. J. Chyle, A. O. Smith Corp.; H. G. Hughey, Air Reduction Sales Co.; V. N. Krivobok, The International Nickel Co.; F. G. Outcalt, The Linde Air Products Co.; A. E. Taylor, Armco Steel Corp.; R. David Thomas, Jr., Arcos Corp.

a solid solution of chromium-nickel-carbon in gamma iron, is non-magnetic in character. The principal effect of nickel in these alloys, in addition to the formation of austenite, is increased high-temperature strength and corrosion resistance.

In addition to the principal alloying elements, chromium and nickel, these steels also contain other elements which affect their properties. Some of these elements, such as carbon and manganese, augment the austenite stabilizing action of the nickel while others, such as molybdenum, columbium and titanium, promote the formation of delta ferrite in the structure and are carbide formers as well. Their action is the same as that of chromium. Silicon is also a strong ferrite-forming element. The austenite and ferrite-forming elements are suitably balanced to meet the requirements of various applications of these alloys.

Table 4 summarizes briefly the effects of these various elements in austenitic chromium-nickel steels.

The austenitic chromium-nickel steels make mechanically satisfactory welds. but under certain conditions they tend to show what is commonly called *weld decay*. When they are heated within the temperature range of 800 to 1600°F. or cooled slowly through that range, the carbon is precipitated from solid solution mainly at the grain boundaries, i.e., intergranularly uniting with chromium to form chromium-rich carbide. The commonly held belief is that the adjacent areas impoverished in chromium have a much lower resistance to corrosion than the remainder of the metal, and under certain corrosive conditions this results in a localized intergranular attack, the severity of which depends on the time and temperature of exposure as well as the composition and prior treatment of the steel.

In the process of welding, the deposited metal and the base metal are brought up to the melting temperature, approximately 2600°F. Hence, with the actual weld itself at the fusion temperature there will be a parallel base metal zone heated to between 800 and 1600°F. This is the zone of carbide precipitation, the degree of which, for any given welding condition, is approximately proportional to the carbon content, the lower the carbon the less the effect.

The 18–8 types will retain a maximum of about 0.02% carbon in solid solution under all conditions. As the carbon con-

Table 2—ACI Designations and Compositions of Austenitic Chromium-Nickel Stainless Steel Castings

Designation	Carbon, %	Chromium, %	Nickel, %	Other Elements, %[a]
CE-30	0.30 max.	26.00–30.00	8.00–11.00	.....
CF-8	0.08 max.	18.00–21.00	8.00–11.00	.....
CF-20	0.20 max.	18.00–21.00	8.00–11.00	.....
CF-8M	0.08 max.	18.00–21.00	9.00–12.00	Mo 2.00–3.00, Si 1.50 max.
CF-12M	0.12 max.	18.00–21.00	9.00–12.00	Mo 2.00–3.00, Si 1.50 max.
CF-8C	0.08 max.	18.00–21.00	9.00–12.00	Cb 8 x C min., 1.00 max.
CF-16F	0.16 max.	18.00–21.00	9.00–12.00	Mo 1.50 max., Se 0.20–0.35, P 0.17 max.
CF-16Fa	0.16 max.	18.00–21.00	9.00–12.00	Mo 0.40–0.80, S 0.20–0.40
CG-12	0.12 max.	20.00–23.00	10.00–13.00	.....
CH-10	0.10 max.	22.00–26.00	12.00–15.00	.....
CH-20	0.20 max.	22.00–26.00	12.00–15.00	.....
CK-20	0.20 max.	23.00–27.00	19.00–22.00	.....
HE	0.20–0.50	26.00–30.00	8.00–11.00	.....
HF	0.20–0.40	18.00–23.00	8.00–12.00	.....
HH	0.20–0.50	24.00–28.00	11.00–14.00	N 0.20 max.
HI	0.20–0.50	26 00–30.00	14.00–18.00	.....
HK	0.20–0.60	24.00–28.00	18.00–22.00	Si 3.00 max.
HL	0.20–0.60	28.00–32.00	18.00–22.00	Si 3.00 max.
HT	0.35–0.75	13.00–17.00	33.00–37.00	Si 2.50 max.
HU	0.35–0.75	17.00–21.00	37.00–41.00	Si 2.50 max.
HW	0.35–0.75	10.00–14.00	58.00–62.00	Si 2.50 max.
HX	0.35–0.75	15.00–19.00	64.00–68.00	Si 2.50 max.

[a] Manganese, 1.50 max. in C grades, 2.00 max. in H grades; silicon, 2.00 max.; sulfur, 0.04 max., phosphorus, 0.04 max., unless otherwise noted. In H grades Mo, though not intentionally added, is limited to 0.50 max.

Table 3—Representative Properties of Wrought Austenitic Chromium-Nickel Steels in Sheet Form[a]

Alloy	17-7	18-8		25-12	25-20	18-8 Mo	18-8 Ti	18-8 Cb
AISI Type	301	302	304	309	310	316	321	347
Condition	Cold-rolled, ½ hard temper	Annealed	Annealed	Annealed	Annealed	Annealed	Annealed	Annealed
Physical Properties								
Density, lb. per cu. in.	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
Magnetism	Magnetic	Non-magnetic	Non-magnetic	Non-magnetic	Non-magnetic	Non-magnetic	Non-magnetic	Non-magnetic
Specific electrical resistance at room temp., microhms/cm./sq. cm.	77	72	72	78	78	74	72	73
Specific heat, Btu /lb./°F., 32–212°F.	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Thermal conductivity, Btu./hr./sq. ft./°F./ft.								
212°F.	8.7	9.4	9.4	8.0	8.0	9.4	9.3	9.3
932°F.	11.5	12.4	12.4	10.8	10.8	12.4	12.8	12.8
Mean coefficient of thermal expansion per °F.								
32–212°F.	9.4×10^{-6}	9.6×10^{-6}	9.6×10^{-6}	8.3×10^{-6}	8.0×10^{-6}	8.9×10^{-6}	9.3×10^{-6}	9.3×10^{-6}
32–1200°F.	10.4×10^{-6}	10.4×10^{-6}	10.4×10^{-6}	10.0×10^{-6}	9.7×10^{-6}	10.3×10^{-6}	10.7×10^{-6}	10.6×10^{-6}
Melting point range, °F.	2550–2590	2550–2590	2550–2650	2550–2650	2550–2650	2500–2550	2550–2600	2550–2600
Mechanical Properties (At normal temp. except as stated)								
Hardness—Rockwell No.	C32	B85	B80	B85	B85	B85	B80	B85
Tensile strength, psi.	150,000 min.	90,000	85,000	90,000	95,000	90,000	90,000	95,000
Yield strength (0.2% offset), psi.	110,000 min.	40,000	35,000	45,000	45,000	40,000	35,000	40,000
Elongation in 2 in., %	15–18 min.	50	55	45	45	50	50	45
Endurance limit (fatigue), psi.	.....	....	35,000	....	....	39,000	....	....
Stress for creep rate of 1% per 10,000 hr., psi.								
1000°F.	.....	17,000	17,000	15,900	17,000	25,000	18,000	19,000
1200°F.	.....	7,000	7,000	8,000	9,000	12,700	8,000	8,200
1500°F.	.....	1,200	1,200	1,000	1,000	2,800	850	1,500

[a] Mechanical properties of strip, plate, bars, etc., may be slightly different from those of sheet.

tent increases to about 0.08% the amount of carbon which can be precipitated slowly increases, but in many cases this is not detrimental to the corrosion resistance. At higher carbon levels carbide precipitation increases rapidly. The low-carbon stainless steels are, consequently, preferred for arc and gas welding. Type 304 with a maximum carbon content of 0.08% is widely used. Recently, extra-low-carbon stainless steels of the 18–8 and 18–8 Mo types, containing a maximum of 0.03% carbon, have become available.

Table 4—Effect of Various Elements in Austenitic Chromium-Nickel Steels

Element	Types of Steel	Effects
Carbon	All types	Promotes the formation of precipitates harmful to corrosion resistance. In so far as possible the carbon should be low for best results in service after welding.
Columbium	347	Primarily to combine with carbon to reduce susceptibility to intergranular corrosion. Grain refiner. Promotes the formation of ferrite.
Manganese	All types	Promotes the formation of austenite.
Molybdenum	316, 317	Improves strength at high temperatures. Improves corrosion resistance to reducing media. Promotes the formation of ferrite.
Phosphorous and selenium, or sulfur	303	Increases machinability but makes welding difficult. Generally lowers corrosion resistance slightly.
Silicon	302B, 314	Increases resistance to scaling. Promotes the formation of ferrite.
Titanium	321	Primarily to combine with carbon to reduce susceptibility to intergranular corrosion. Grain refiner. Promotes the formation of ferrite.

Figures 1 to 5 show the effect of carbide precipitation detected by macro-etching with nitric-hydrofluoric acid solution, and by microscopic examination of specimens etched electrolytically. Figure 1 shows two pieces of 18–8 steel (Type 302) welded to two pieces of 18–8 S (Type 304). The pieces marked *A* (right) have been subsequently heat treated at 1950 to 2050°F., and the other pieces (left) are in the as-welded condition. All pieces have been etched with hot nitric-hydrofluoric acid solution. Note the *weld decay* or corroded zone caused by carbide precipitation alongside the weld in the 18–8 (Type 302) as-welded piece. The corresponding zone in the other piece is practically free from corrosion. Note also that in the heat-treated weld both steels are completely free from the corrosion-affected zone, showing that the precipitated carbides have gone back into solution. Figure 2 is a photomicrograph of a section through 18–8 stock prior to welding. Figure 3 is a photomicrograph of a section through the heat-affected zone of 18–8 S stock in the as-welded condition. Figure 4 is a photomicrograph of a section through the heat-affected zone of 18–8 stock in as-welded condition, and Fig. 5 is a photomicrograph of a section through the same zone as in Fig. 4, but after heat treating. Note the presence of carbides along the grain boundaries in Fig. 4.

Carbide precipitation in austenitic weld metals will be found in grain boundaries or around and within ferrite patches if they exist. Although a single bead of weld metal usually does not show evidence of carbide formation because of the rapid cooling from molten temperatures, the heat effect from subsequent beads in multiple-pass deposits will show bands of carbide precipitation within all but the last pass of weld metal. Intergranular corrosion resulting from carbide precipitation is generally much less when ferrite is present because many carbides precipitate within ferrite patches and correspondingly fewer at the grain boundaries. Weld metals containing columbium are relatively free from intergranular carbides, even in multipass welds, because of the stabilizing effect of columbium which forms carbides more readily than chromium.

Compositions which in wrought form will be found to be fully austenitic will often show the presence of small islands of delta ferrite in an austenite matrix in the cast or weld metal form. Figures 6 and 7 show the microstructure of typical fully austenitic weld beads and those containing some delta ferrite.

The presence or absence of ferrite in a weld metal structure will depend principally on the composition. Since many of the corrosion-resistant stainless steels are borderline with respect to phase distribution, a single type of weld metal may be fully austenitic or partially ferritic depending upon the *composition balance*. may, however, develop in alloys which are initially entirely austenitic. No sigma phase has been observed in compositions such as 18–8, Types 302 and 304, even where ferrite has been present, but it has been encountered in alloys high in titanium, columbium, molybdenum, silicon or chromium. The sigma phase may cause

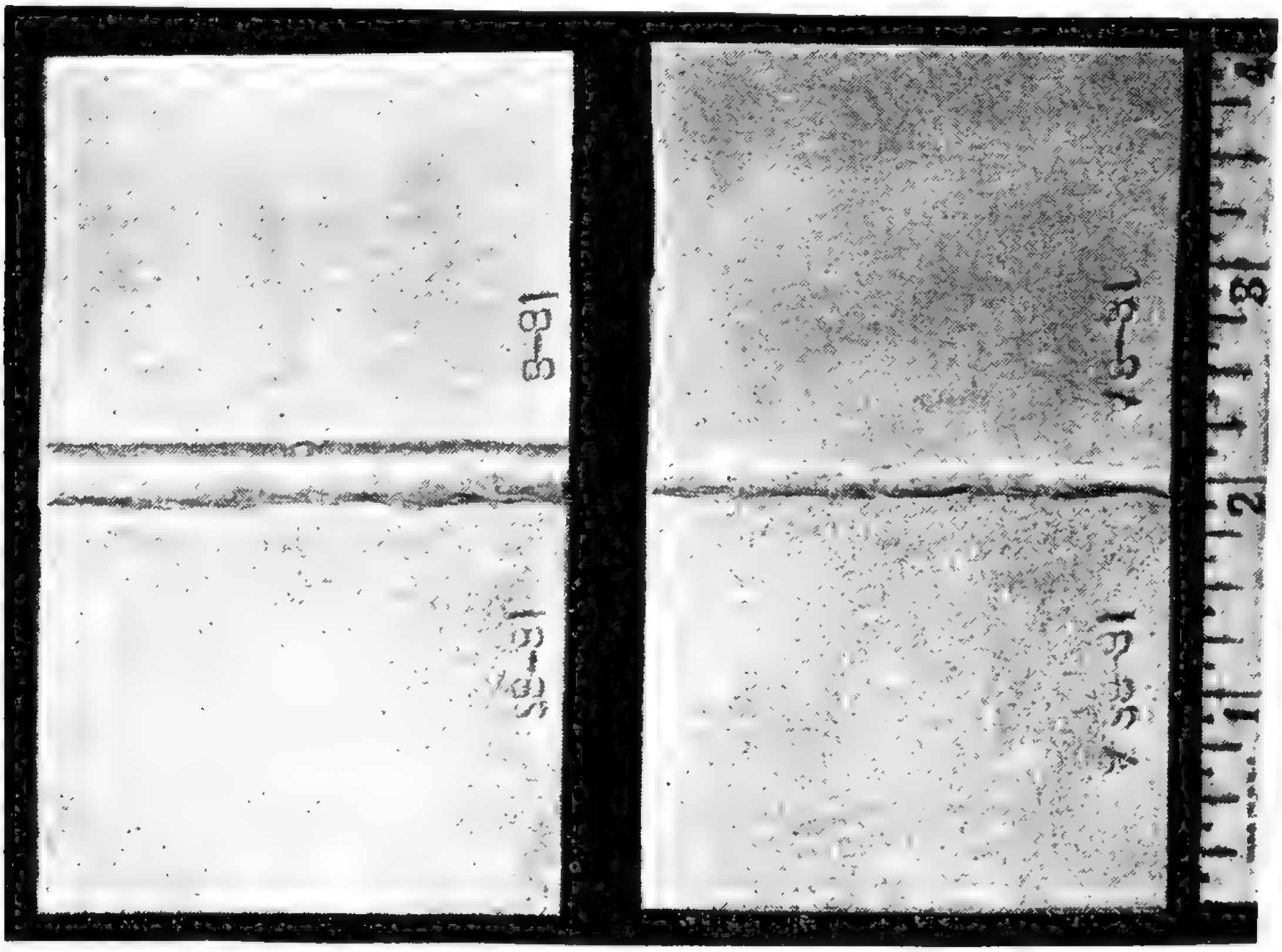


Fig. 1.—Type 302 (18–8) Steel Arc Welded to Type 304 (18–8S) Steel

(Left) As-welded and macro-etched. Note corroded zone in Type 302 adjacent to weld. (Right) Annealed. Note absence of corroded zone.

An indication of the constitution of a given weld metal may be obtained by referring to the diagram in Fig. 8.

Fully austenitic weld deposits are occasionally susceptible to hot-short cracks. The presence of ferrite in the weld structure appears in many cases to inhibit this tendency.

Besides the austenite, ferrite and carbides commonly found in chromium-nickel stainless steels, an intermetallic compound called the *sigma phase* is occasionally encountered. This phase is usually formed as a transformation from ferrite by holding the steel for long times at temperatures ranging from about 1200 to 1700°F., depending on alloy content. It loss in ductility, impact resistance and corrosion resistance. Although a long time at elevated temperatures is usually required to promote this phase, evidence of sigma has been occasionally reported in weld metals in the as-welded condition.

There are several methods that can be used to combat intergranular corrosion in a weldment made from an austenitic chromium-nickel steel.

One such means of removing susceptibility to intergranular corrosion resulting from welding is by appropriate heat treatment of the welded structure when feasible. Another effective means of preventing intergranular corrosion is by the suitable addition of either titanium or colum-

500 ×

Fig. 2.—18–8 Unwelded Base Metal

500 ×

Fig. 3.—18–8S Base Metal As-Welded

500 ×

Fig. 4.—18–8 Base Metal in Heat-Affected Zone
Note carbides; compare Fig. 2.

500 ×

Fig. 5.—Section Shown in Fig. 4 After Heat Treating

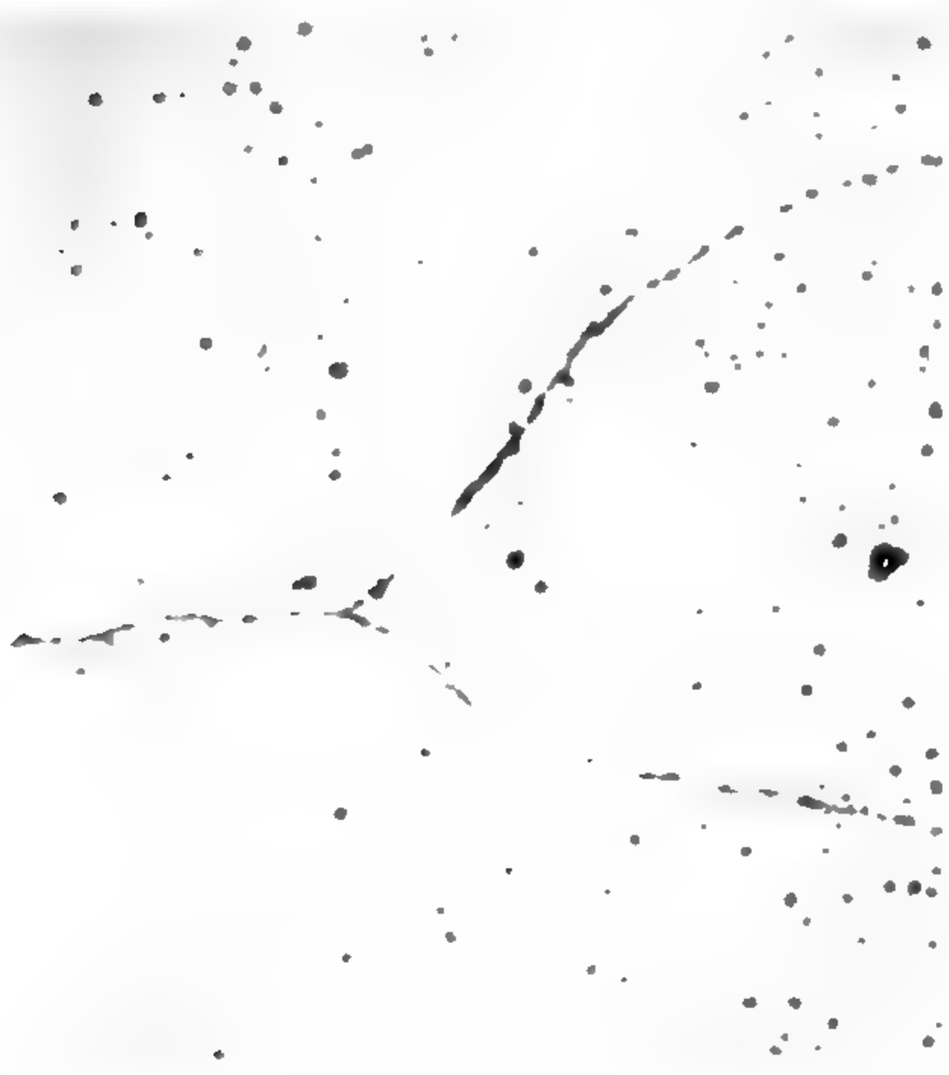


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Fig. 6.—Microstructure of Weld Metal Deposited from an E310 Electrode

Note single phase austenitic structure.

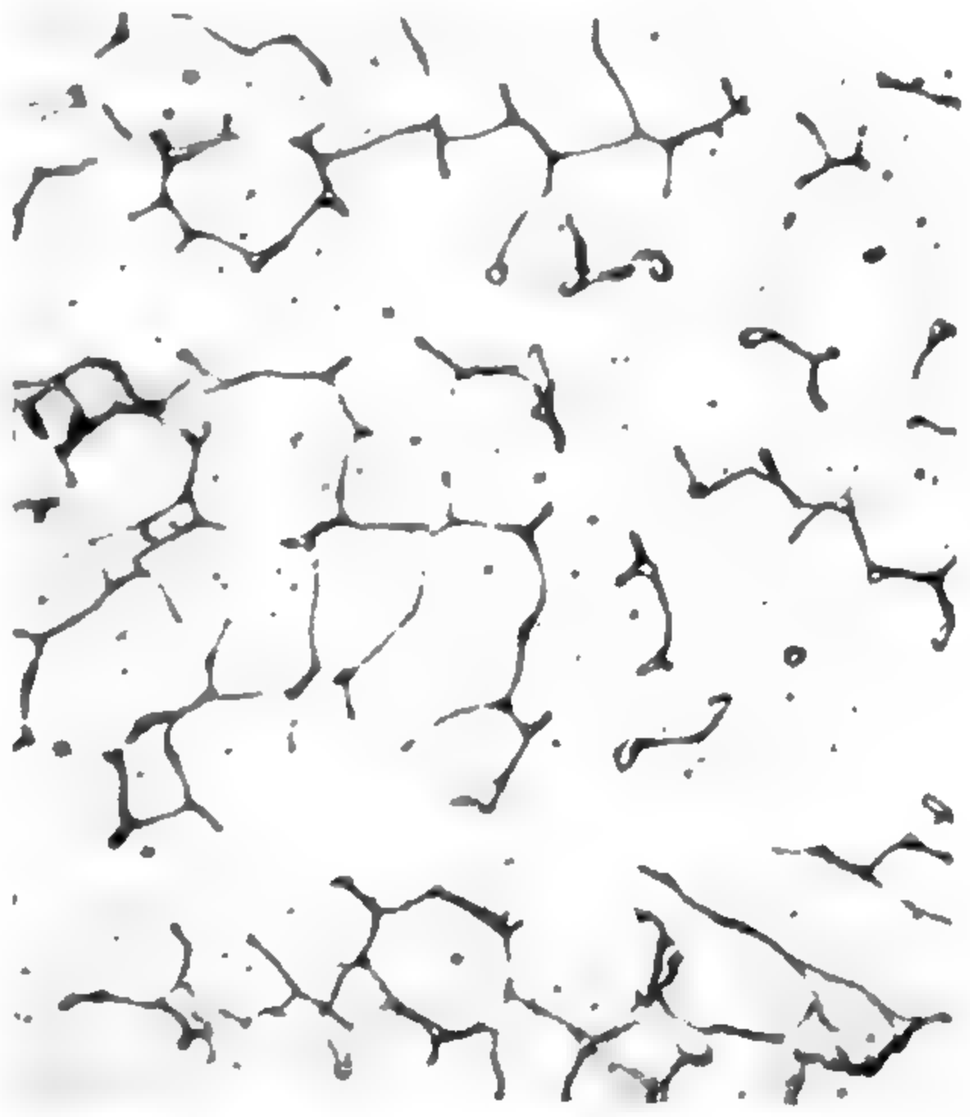

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Fig. 7.—Microstructure of Weld Metal Deposited from an E308 Electrode

Note duplex structure of austenite as matrix containing dendritic pools of delta ferrite.

bium. As noted in Table 4, these elements tend to fix the carbon by forming titanium or columbium carbides thereby preventing the formation of chromium carbide when the metal is heated between 800 and 1600°F. Structures of these stabilized types (321 and 347), properly welded, have given excellent results. One important application is heat- and corrosion-resisting alloys for service between 800 and 1550°F.

described in Chapter 59, there are a few special methods or requirements applicable primarily to these alloys.

Determination of Weld Metal Composition.—This is sometimes required (as in ASME Boiler Code Interpretation: Case 897) to insure approximate uniformity of composition throughout the joint when such uniformity is vital to the performance of the joint in service where corrosion is involved.

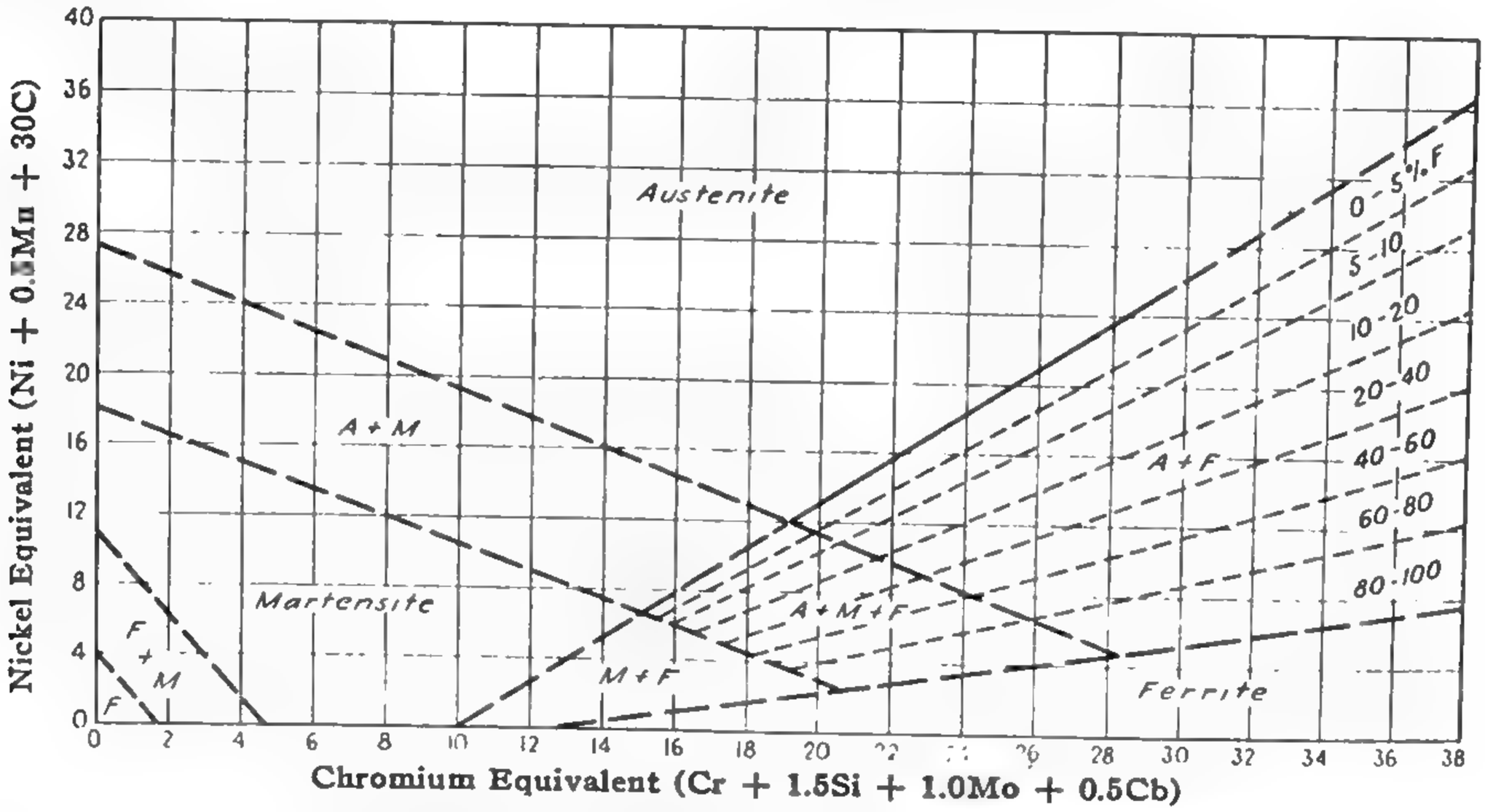


Fig. 8.—Phase Diagram for Weld Metal in the As-Welded Condition

The microstructure of a weld can be predicted by calculating the chromium and nickel equivalents from the composition of the weld metal and applying the formulas shown. The resultant point is then plotted on the diagram and the phase field in which it falls is noted.

In the fabrication of weldments of unstabilized types which will not be heat treated after welding, it is important to recognize the influence of the welding process on the time during which any part of the weldment is in the damaging temperature range. This time includes heating, holding and cooling times. In general the welding processes may be arranged in order of increasing weld time as follows: spot and seam welding; shielded metal-arc welding; submerged arc welding; oxy-acetylene or other gas welding. Thus, for a given carbon content in any unstabilized type and thickness, the degree of carbide precipitation and resulting susceptibility to intergranular corrosion tend to be least in spot welds and greatest in gas welds.

Methods of Testing

In addition to the usual test methods applied to welded joints and weld metal,

Intergranular Corrosion Test.—This is a test to determine the susceptibility of the welded joint or weld metal to intergranular corrosion in a solution capable of corroding the grain boundary regions of metal sensitized by the heat of welding. Intergranular attack is detected by examination of a bent or twisted surface, by measurement of the change of electrical resistance resulting from intergranular corrosion or by microscopic examination of a polished cross-section after the corrosion test. The test requirements in Case 897 of the ASME Boiler Code Interpretations are cited as a typical example.

> "The free-bend test specimen shall be ground and polished. Immerse in a boiling copper-sulphate sulphuric-acid solution for a minimum of 72 hours. This solution shall consist of 47 cc. concentrated sulphuric acid and 13 gm. of crystalline copper sulphate ($CuSO_4$·-

$5H_2O$) per liter of water. The sample shall be bent so as to confine the bend to a point $^1/_4$ in. from the edge of the weld in the base metal, and the least elongation in the outer fibers measured across the weld shall be not less than 20%. After bending, the metal shall show no sign of disintegration."

There are two other common procedures, one employing nitric-hydrofluoric acid and the other, boiling nitric acid, to detect weld decay.

The former makes use of a solution consisting of 10 to 20% nitric acid plus 2 to 4% hydrofluoric acid, the balance water. This solution is used at a temperature of 180°F. and is very drastic as well as rapid. The solution attacks the base metal in the zone where precipitated carbides are present. The attack is very severe and if the carbides are present in any considerable quantity only a few minutes are necessary to sever the specimen alongside the weld where the stock is $^1/_{16}$-in. thick or less. A specimen with no carbides present will show a uniform attack throughout. Where the carbides are present in greatest number, the attack will show up first as a slight discoloration, and then as a somewhat sandy condition which will steadily increase to the point where grains of the metal can actually be rubbed loose with the finger.

Four periods of $^1/_2$ hr. each in the nitric-hydrofluoric acid test are generally sufficient. However, the results, especially in borderline cases, may be somewhat difficult to evaluate for those who have not had previous experience. As in all such tests, the investigator must know how to interpret the results of the test and to determine whether the steel will be satisfactory under the service conditions proposed.

The Huey test employs a solution of boiling 65% nitric acid. The specimen is immersed for five 48-hr. periods, each time in a fresh solution whose concentration is kept constant by use of a reflux condenser over the test flask. The weight loss of the specimen is determined after each period. Tentative methods for the conduct of this test are described in ASTM *Recommended Practices for Boiling Nitric Acid Test for Corrosion-Resisting Steels* (A262–44T).

The data from this test are commonly reported in terms of inches of loss of metal from the surface per month or year. This assumes a uniform rate of attack over the whole specimen, a condition which may not always exist, especially in specimens containing welds; consequently, care must be used in the interpretation of the data. It must also be recognized that this and the other test solutions mentioned may attack other constituents than precipitated carbides. Careful macroscopic and microscopic examination of the test specimen in cases of this kind should be considered.

Microscopic Examination.—This type of examination may be used to determine the presence of precipitated carbides in as-welded specimens (see Fig. 4) or, as noted above, to establish the character of corrosion attack in test solutions.

The specimen should be highly polished by standard metallographic procedures and then electrolytically etched by immersing as the anode in a solution consisting of 10 gm. sodium cyanide in 90 cc. of distilled water. The cathode used should be a section of the same or similar material. The general practice is to space the electrodes about 1 in. apart and use an etching time of 5 minutes. Current from a regular 6-volt automobile storage battery is entirely satisfactory for the test.

The specimen should be removed, rinsed in hot water and dried in a mild air blast so as not to stain. It should then be examined under the microscope at 500 or 1000 diameters. The carbides will appear as short or round globules encircling the grain structure and will be present in varying quantities governed by the amount of carbon in the parent metal. Highly cold-worked material will also show carbides that have precipitated on the slip planes.

NOTE: Nitric and hydrofluoric acids are strong acids and great care should be used in handling. Use approved safety goggles and rubber gloves, making sure they do not leak. Sodium cyanide and its solutions are highly poisonous and should not be brought in contact with open wounds. This salt reacts with acids to produce an extremely lethal gas.

Here again it is important that the investigator know how to interpret his laboratory findings in terms of actual service conditions. After all, there are many fabricated articles of austenitic

chromium-nickel material which are giving excellent service despite the fact that precipitated carbides are present in the section which has been affected by the heat from the welding operation.

Treatment After Welding

Heat Treatment.—The necessity for heat treatment of austenitic chromium-nickel steel weldments depends to a great extent upon the service conditions to be encountered. For some applications heat treatment is used to impart the greatest degree of corrosion resistance that is possible to attain, while for other applications heat treatment for stress relieving only is necessary.

In weldments of stainless steels corrosion is generally localized in the heat-affected zones adjacent to the welds where carbides are precipitated. The heat-affected zones can usually be completely eliminated by suitable annealing heat treatments, which result in complete solution of the carbides (see Fig. 1). Where maximum corrosion resistance is required, such treatment is recommended.

For annealing, suitable equipment must be on hand which is capable of heating the entire structure to a temperature range between 1900 and 2050°F. Sufficient time should be allowed to make sure all parts of the structure are up at temperature, and that the carbides are in solution. Holding at temperature for at least 1 hr. per in. of maximum thickness and in no case less than $^1/_2$ hr. is recommended. The subsequent cooling operation must be rapid, particularly through the range from 1700 to 1000°F., in order to hold the carbon in solution once it has been restored by the annealing treatment. Thicknesses of $^1/_8$ in. and lighter can usually be cooled in air. For greater thicknesses than this more drastic cooling such as plunging directly into water or water-spray cooling is normally recommended. The cooling rate required to hold carbides in solution depends largely on the carbon content of the material. The lower carbon alloys can be cooled at slower rates than the higher carbon grades. The cooling method will also depend on the thickness of the part and the design of the section to avoid warpage.

In some cases the problem of stress corrosion is encountered, and for that reason the weldments must be stress relieved. Stress relieving of the stabilized stainless steel alloys can be accomplished by heating the weldments to a temperature of 1375°F., holding for 1 hr. per in. of thickness, followed by air cooling. This treatment is recognized as not being sufficiently high in temperature to completely remove all of the fabricating stresses, but it does reduce the magnitude of the high stresses and has been found to be practical for some applications.

The degree of stress relief afforded by heat treatment depends to a large extent on the temperature used. For austenitic stainless steels, treatment at approximately 1375°F. relieves about 50% of the fabricating stresses. Treatment at 1600 to 1650°F. relieves approximately 90% of the stresses. For some of the unstabilized stainless steel alloys, stress relieving at temperatures of 1300°F. or higher can be carried out satisfactorily, provided that adequate corrosion tests are made after this treatment to insure against excessive loss in corrosion resistance from heating in this temperature range.

Pressure vessels which are built under the ASME Boiler Code are generally heat treated according to the requirements of Case 897. This case prescribes three distinct heat treatments after welding for the various types of stainless steel austenitic materials. (Refer to ASME Case 897, latest revision.)

For some alloys containing columbium or titanium a stabilizing heat treatment may be specified, which at the same time also serves as a stress-relieving heat treatment. The stabilizing temperature range is generally from 1550 to 1650°F. and the weldment is heated for a period of 2 hr. per in. of maximum thickness and allowed to cool in still air or in the furnace.

Cleaning and Passivating.—After the welds are completed, all welding flux, scale and heat tint should be removed by grinding, pickling, sandblasting or other approved methods. If the structure is to be annealed, the welding flux must be removed from the surface before heating in the furnace.

If the welds are to be ground flush with the parent metal, all rough grinding can be done using rubber or bakelite bonded wheels and set-up wheels, with abrasive and binder, using polisher's tallow as a lubricant. Dry grinding invariably produces considerable heat and tends to leave a surface that is oxidized. This, as soon

as it becomes moist, usually discolors, taking on a yellowish-brown tint.

All producers of stainless products exercise great care throughout all their operations to prevent iron contamination on the surface of the material. This same care should be used by the fabricator from the time the material arrives in the plant until it is delivered and installed in the customer's plant.

If iron contamination is known to be present, or if the fabricator wishes to make sure that it is not, small parts can be immersed in a 15 to 20% solution of nitric acid at approximately 140°F. The parts should be rinsed clear of acid with hot water and then dried. This is generally termed *passivating*. The iron is dissolved and the material assisted in building up its corrosion-resisting surface. Large pieces of equipment can be filled with this acid or swabbed down several times, then rinsed clear of acid and dried.

pass into the slag resulting in weld metal deficient in corrosion resisting properties. Carbonaceous materials must be avoided in the fluxes or gas stream in order to avoid an undesirable increase in carbon in the weld metal. Moisture must be held to a minimum, since it contributes to weld metal porosity. Fluxes as used in the shielded metal-arc and submerged melt processes must have adequate fluidity and dissolving power to fuse undesirable oxides from the molten metal.

Bare metal-arc welding is not applicable to stainless steels since the arc is difficult to maintain, and the weld metal will not be of proper composition nor will it fuse properly with the base metal.

The influence of heat treatment on the mechanical properties of Type 308 (18–8) weld metal in comparison with cast and with wrought material of the same composition is shown in Table 5.

Shielded Metal-Arc Welding.—The

Table 5—Influence of Heat Treatment on Mechanical Properties of 18–8 Weld Metal Compared with Cast and Wrought 18–8

Material and Type	Treatment	Tensile Strength, Psi.	Yield Strength, Psi.	Elongation in 2 In., %	Izod Impact, Ft.-Lb.
Weld Metal E308	None	79,000	51,000	45	65
	Annealed	74,000	40,000	45	81
	Sensitized	75,000	40,000	46	90
Ingot 308	None	66,000	29,000	58	106
	Annealed	66,000	33,000	63	111
	Sensitized	67,000	31,000	56	101
Bar 308	None	85,000	47,000	58	120
	Annealed	79,000	36,000	62	120
	Sensitized	79,000	35,000	63	120

Weld Metal specimens from 2 × 5 × 11-in. block deposit. Ingot specimens from center of 11 × 11 × 60-in. ingot. Bar specimens from 3/4-in. diam. bar rolled from ingot. Annealing Treatment: 15 min. at 1950°F., water quenched. Sensitizing Treatment: Annealed plus 4 hr. at 1200°F., air cooled. Tensile Specimens: Standard 0.505-in. diam.

HOW TO WELD

Arc Welding

Austenitic chromium-nickel steels readily lend themselves to fabrication by means of welding. Of the various processes available, there are four which are by far the most commonly employed: shielded metal-arc welding; atomic hydrogen welding; inert-gas metal-arc welding; and submerged arc welding. In all four of these arc-welding processes the protection of the molten weld metal from atmospheric oxidation is of paramount importance. Unless adequate protection is provided, certain essential alloying ingredients may become oxidized and thus

American Welding Society and American Society for Testing Materials have established seven series of classifications of austenitic chromium-nickel arc-welding electrodes, namely, Series E308, E309, E310, E316, E317, E330 and E347. Their chemical compositions are described in Chapters 38 and 61. While these seven series of electrodes are intended to serve for shielded metal-arc welding the principal grades listed in Tables 1 and 2, other types are also available. It will be noted that the alloy content of the weld metal is generally above the minimum of the corresponding base metal to insure that the general corrosion resistance of the weld metal will be at least equal to that of acceptable base metal. The absence of

an E321 electrode is accounted for by the fact that titanium is very difficult to recover in the weld metal and therefore Type 321 steels are generally welded with E347 electrodes. There is no E303 electrode owing to the tendency to cracking or excessive porosity caused particularly by high phosphorus or sulfur contents.

Most electrodes are designed for use with d.c. reverse polarity. The electrode coating for d.c. welding may be any of the usual types: lime, lime-titania or titania. When a.c. is employed, titania-type electrode coatings are usually required. The recommended current ranges are lower than those employed in ordinary steel welding (see Table 6).

Table 6—Recommended Current Ranges for Austenitic Chromium-Nickel Electrodes

Electrode Size, In.	Current, Amp. Flat, Horizontal and Overhead	Current, Amp. Vertical	Maximum Arc Voltage
2/64	15– 25	15– 25	23
1/16	25– 40	25– 40	24
5/64	35– 55	35– 55	24
3/32	45– 70	45– 65	24
1/8	70–105	70– 95	25
5/32	100–140	100–125	26
3/16	130–180	130–145	27
1/4	210–290	.....	28
5/16	250–400	.....	29

It is desirable to keep the arc length as short as possible, not exceeding the voltages indicated in Table 6.

Electrodes are available for welding in all positions in sizes up to and including 5/32-in. diameter. Certain types of electrodes may be used in 3/16-in. diam. in all positions. Some electrodes are designed for use only in the flat and horizontal-fillet positions, so that when position welding is required, the proper classification of electrodes must be specified. (Typical tensile properties of weld metal from metal-arc weld deposits are shown in Chapter 61.)

The preparation of the joints to be welded is very important. All grease, paint or other foreign matter must be removed to prevent carbon pickup and inclusions in the deposited weld metal. Where long seams are to be welded it is important that the fitup be accurate and suitable clamping or holding devices be provided to minimize warping.

In this connection it should be pointed out that the chromium-nickel stainless steels have a coefficient of expansion as much as 50% higher than mild steel and a thermal conductivity about one third as great; consequently, root openings should be increased. Backing plates of copper placed closely to the weld zone help remove heat and minimize distortion. Rigid, well-designed jigs or fixtures are recommended to hold parts in alignment. Parts show a minimum distortion when allowed to cool in the fixture.

In cases where fixtures cannot be employed, closely spaced tack welds should be employed which can be peened before further welding to align the weldment. For complicated assemblies a planned sequence of welding operations is necessary. The backstep and block sequences are recommended on sheet, strip and plate assemblies.

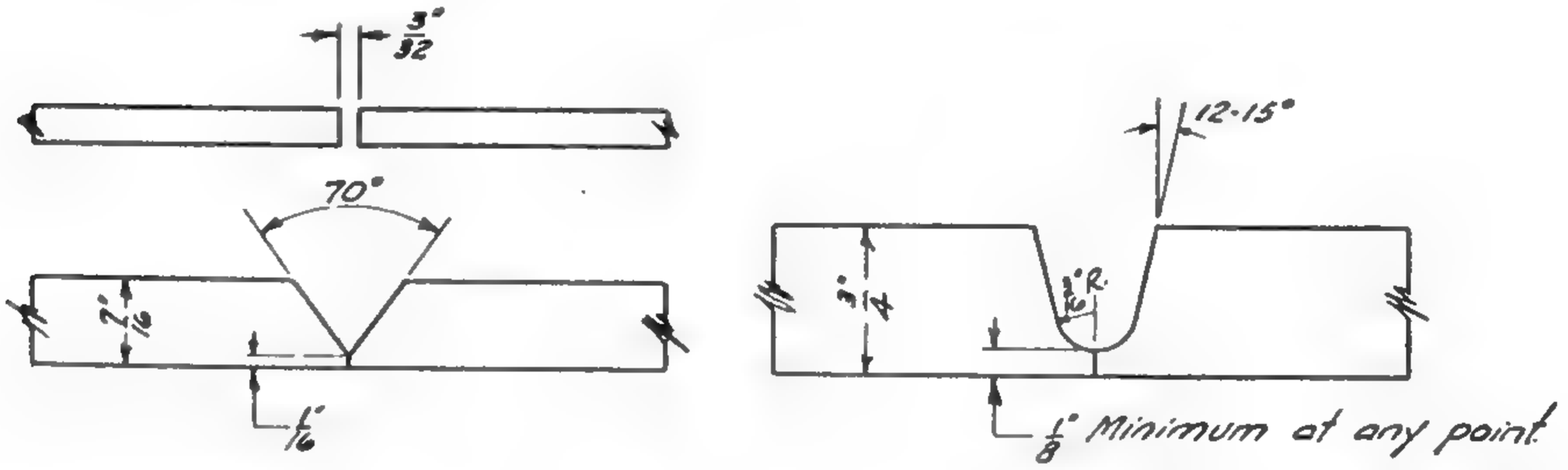
On plate material, to secure proper fitup and sound welds it is necessary that the abutting edges be prepared by machining to provide a suitable groove for welding. On plate 3/16-in. thick and less a square planed or sheared edge is generally used. On plate from 3/16 in. to 1/2 in. in thickness the edges are usually beveled and on thicker material the U groove is considered best. Figure 9 (*a*), (*b*) and (*c*) shows the details of edge preparation for the respective thickness ranges.

When several beads of welding are required it is advisable to use a number of light beads rather than to try to fill the groove in one or two passes, because of the danger of shrinkage cracks and decreased corrosion resistance. String beading rather than weaving is desirable.

The weld should be thoroughly cleaned with a blunt tool and then with a stainless steel brush before depositing successive beads. In all multiple-pass welds, the root pass should be ground or chipped out from the back down to clean, solid metal, after which the back weld is deposited if the groove is single vee or U. An alternate layer sequence is used between opposite sides of a double-vee or U-groove. In most stainless electrodes, the deposition efficiency will be about 75% when normal currents and voltages are employed. Stub losses will vary widely in different shops and under different conditions, but when held to a minimum, 9-in. electrodes (3/32-in. and smaller diameters) will show about 10% stub loss, and

14-in. electrodes ($^1/_8$-in. and larger diameters) will show about 7% stub loss. (See Chapter 41 for further information.)

Atomic-Hydrogen Arc Welding. — Atomic-hydrogen welding (see Chapter 11) is invaluable in the welding of light-gage material and produces an extremely smooth weld. However, because of the intensity of the heat produced by this process, it is important that the work be suitably clamped and tack welded so that distortion will be minimized. The thickness of the stock will generally indicate whether filler metal is required to build up the full thickness of the weld section.



(*a*) For plate $^3/_{16}$ in. and thinner

(*b*) For plate $^1/_4$- to $^7/_{16}$-in. thick

(*c*) For plate $^1/_2$ in. and thicker

Fig. 9.—Edge Preparation for Arc Welding

On light sheet gages, 0.050 in. and less, the butt joints can be made by having the edges fit tightly against each other without the use of any added filler metal. Where a slight reinforcement is necessary on lighter gages, the abutting edges can be bent up slightly or flanged to provide for added weld metal. On heavier work, it is customary to use welding rods of the same type of analysis as the base metal to provide for ample weld reinforcement.

The backing for atomic-hydrogen welding is important and may consist of either gas, copper strip or flux painted on the underside of the edges. For light gages and where avoidance of discoloration on the underside is important, hydrogen gas is introduced in a groove directly below the abutting edges. A small amount of gas is introduced in the groove directly below the joint, which prevents air from coming in contact with the heated weld metal. For some applications a plain copper bar is used as a backing, with or without a groove, depending on the extent of the penetration desired. The copper bar must be clean, and in some cases chromium plating of the copper bar is recommended. In some applications the use of a flux on the underside of the weld is recommended. It is important, however, that the flux does not contain boron-containing ingredients which might react with the weld metal, causing brittleness and cracking. The flux is generally recommended where gas backing cannot be used or where a tightly fitting backing bar is not practical. The action of the flux backing on the underside helps to prevent the molten metal from dripping through the seam.

The free-machining stainless steels containing sulfur and selenium cannot be satisfactorily welded by this process because of severe porosity in the weld metal. Some porosity also may occur with other grades of stainless steel and in cases where welds must be of the highest quality the base metal should be subject to preliminary testing to insure freedom from this condition.

The atomic-hydrogen welding process is widely used in the manufacture of light-gage tubing made from strip stock. It is also used for the welding of light-gage tubes to heavy tube sheets in heat exchangers.

The atomic-hydrogen process is adaptable to various thicknesses of stainless steel but its greatest application is for the welding of stainless steel in thin sections, varying in range from 0.010 in. to approximately $^1/_8$ inch.

Inert-Gas Metal-Arc Welding.—This welding process (see Chapter 12) is

highly recommended for a wide range of thicknesses of austenitic chromium-nickel stainless steels. It is particularly useful in welding materials which are to be ground and polished as there is no spatter or flux to be removed and the amount of weld reinforcement can be easily controlled. Sheet material as thin as 0.015 in. or less may be manually welded if the work is securely jigged. Sheet as thin as 0.005 in. is welded by machine only. While inert-gas metal-arc welding has not been extensively employed on material thicker than $^1/_4$ in., limited use indicates that excellent quality and welding rates comparable to those obtainable with the shielded metal-arc process are possible on thicknesses up to and including $^1/_2$ inch. The process is well suited to casting defect repair because of the ready control of the weld contour and the freedom from danger of flux entrapment.

Although for general-purpose welding, base metal composition is used in the welding rod, variation from this is necessary for specific purposes. Where maximum corrosion resistance is required without postweld heat treatment, Type 347 rod should be used for Grades 301, 302, 304, 308, 321 and 347. For maximum low-temperature impact strength in Type 304 weldments, Type 309 filler metal should be used. Hot-cracking tendency in the stainless steels of high nickel content can be reduced by the use of string beads instead of weave beads. Where this is not sufficient a welding rod of lower nickel content, such as 29–9 (29 Cr–9 Ni), Type 312, and 29–9 Mo (29 Cr–9Ni–2.5 Mo), Type 312 Mo, is frequently used.

Either a.c. or d.c. may be used. With a.c. a high-frequency stabilizing current, if superimposed, will aid in starting and maintaining an arc. Tungsten electrodes should be used. Where d.c. is employed straight polarity is recommended. Carbon electrodes are sometimes used in this case but the possibility of contamination of the weld metal by carbon exists.

Procedures and precautions for preparation of plate and control of distortion in welding by the inert-gas metal-arc process are similar to those already described for shielded metal-arc welding with a few exceptions. The penetration obtained in the inert-arc process makes a root opening unnecessary. In all cases the edges to be welded should be fitted so that they are in contact so far as practical. Where multiple passes are used, preceding beads need be cleaned with a stainless steel wire brush only.

For machine welding of all materials less than $^5/_{16}$-in. thick, accurate and strong jigs are required. For manual welding, jigs are generally essential when fabricating sheet thinner than 0.040 to 0.065 inch. Jigs maintain the edges being welded in proper position and alignment and minimize distortion. Copper backing bars and copper clamp faces remove heat rapidly from the work, resulting in less distortion than in the cases where no bars are used. Where jigs are not used some control of distortion may be obtained by pasting wet asbestos paper in strips parallel to and along each side of the weld zone.

Where the material is adequately jigged, tacking of the material before welding is not necessary. Where no jigs are employed, tacking will be required. All tacking should be done using only the inert-arc process to avoid contamination by flux. In general, tacking requirements are somewhat less than for shielded metal-arc welding. For $^1/_8$- to $^1/_4$-in. plate, $^3/_4$-in. long tacks on 3- to 4-in. centers, and for $^5/_{16}$- to $^1/_2$-in. plate, 2-in. long tacks on 8- to 12-in. centers will usually be satisfactory. All tacks should be wire brushed before final welding. All passes should be brushed before starting subsequent passes.

Submerged Arc Welding.—The blanket of molten slag employed in this process for protecting the weld metal from oxidation provides efficient transfer of readily oxidizable elements. Electrodes used usually have slightly higher chromium and columbium contents than the corresponding type base metal to take care of the small losses that do occur. Powdered metals may also be added to the granulated flux to compensate for losses by oxidation, or to modify the alloy composition of the weld deposit.

This process makes use of high welding currents and is capable of deep penetration and fusion into the members being joined. By virtue of this the resultant weld may be made up of at least one-half base metal and in heavier thicknesses even up to two-thirds base metal. Under normal conditions where dissimilar metals are joined, each component, includ-

Table 7—Typical Double-Vee Butt Joints for Submerged Arc Welding

Thickness, In.	Backing Pass: Groove Angle, Deg.	Root Face, In.	Welding Rod Diam., In.	Current, Amp.	Voltage, Volts	Speed, In./Min.	Finishing Pass: Groove Angle, Deg.	Welding Rod Diam., In.	Current, Amp.	Voltage, Volts	Speed, In./Min.
3/8	90	1/4	3/16	525	30	20	90	3/16	575	32	24
1/2	90	1/4	3/16	700	35	18	90	3/16	900	33	18
5/8	90	1/4	3/16	700	33	16	90	1/4	900	35	12
3/4	90	1/4	1/4	700	33	15	90	1/4	950	35	12
7/8	90	5/16	1/4	715	33	15	90	1/4	1025	35	12

ing electrode, will contribute about one-third of the metal contained in the weld deposit. If one of the base metal pieces is a plain-carbon or low-alloy steel, there is a danger that the alloy content of the weld bead will be reduced by dilution to an undesirably low level unless, of course, an electrode of high total alloy content is selected to compensate for the dilution. As an example, Type 302 (18 Cr–8 Ni) stainless steel plate would be welded to plain-carbon steel plate with a Type 310 (25 Cr–20 Ni) stainless steel welding rod.

Because of the deep penetration characteristic of this welding process, much smaller grooves and root openings are used than with other arc welding processes, thus minimizing the edge preparation and the consumption of welding rod. The deep penetration results in more uniform temperature between the top and bottom surfaces of the base metal at the joint with less pull up and distortion. All thicknesses of material from 16 gage and up can be welded by this process. As in other welding processes, consideration must be given to the possibility of intergranular carbides being precipitated by the heat of welding. So far, complete success has not been obtained in welding light-gage stabilized Type 321 and Type 347 stainless steels, 8 gage and lighter, due to cross checking or cracking in the weld metal. There has been considerable commercial application of the process to light and heavy gages in Type 302 and Type 304 and to heavier gages in a special Type 309 containing columbium as well as Types 316 and 347.

Joint designs customarily used in the submerged-arc welding of plain-carbon steels and currents of approximately 80% of values used for plain-carbon steels of like thicknesses are required (see Chapter 13). Typical welding conditions for butt joints are given in Table 7. The mechanical properties of various weld metals at both room temperature and subzero temperature are given in Table 8.

Close control of weld composition, high speed of welding and uniformity of welds are important factors in making satisfactory submerged-arc welds in stainless steels. Deposits which are free from frequent starts and stops and uniform

Table 8—Typical Mechanical Properties of Submerged Arc Welds

Material	Type 301		Type 347		Type 309 + Cb
Test Plate Thickness	7/8 In.		1/4 In.		1/8 In.
	As-Welded	Water Quenched from 1950°F.	As-Welded	Stress Relieved at 1550°F.	As-Welded
All-Weld-Metal Tensile Test					
Yield point, psi.	41,000–43,500	31,000-44,000	43,900–45,000	37,500	41,800
Ultimate strength, psi.	83,000–84,800	83,000–97,500	83,400–84,500	87,000	80,000
Elongation, % in 2 in.	51–55	49–58	38–41	46	45
Reduction of area, %	60–62	43–65	44–52	60	54
Charpy Impact, Ft.-Lb.[a]					
Notch on Center of Weld					
Room temperature	38	36	31	28	32
−320°F.	26–30	28	17	17	..
Notch in Heat-Affected Zone					
Room temperature	55	50-63	41	36	..
−320°F.	36–42	41–47	47	27	..
Free bend elongation, %	43–52	49–54	40	..	60

[a] Each value average of 3 to 9 tests. Specimens, 10 x 10 mm., prepared according to Paragraph U-142 of ASME Boiler Code.

as to width and composition show excellent resistance to corrosion. High welding speeds are favored to minimize carbide precipitation adjacent to the weld.

Oxy-Acetylene Welding.—This process is more generally used for welding sheets 20 gage or lighter although heavier gages can also be handled.

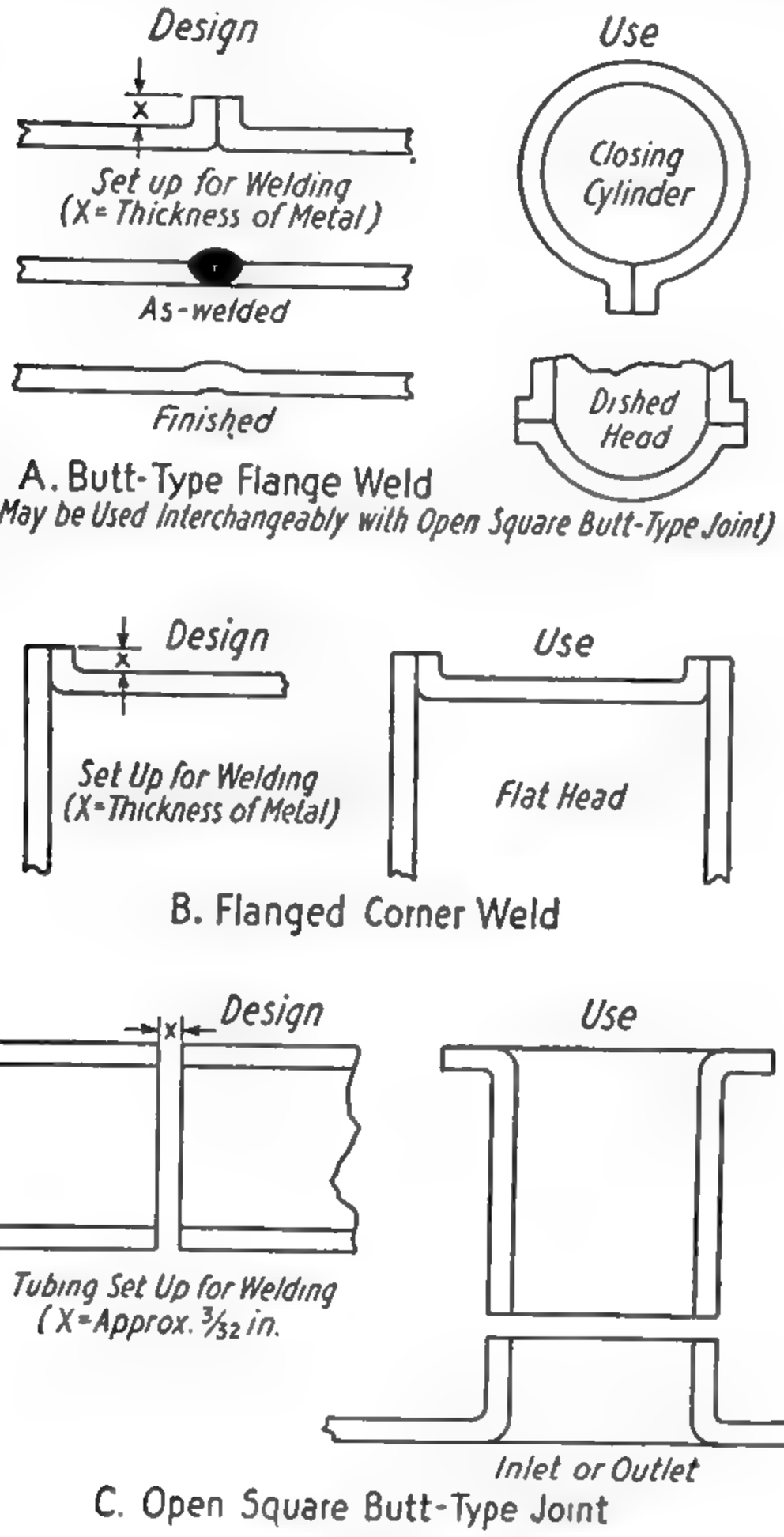


Fig. 10.—Joint Designs for Oxy-Acetylene Welding and Their Use

The degree of carbide precipitation depends upon the heat input during welding, the cooling rate of the heat-affected zone after welding and the composition of the base metal. When proper consideration is given these factors, the corrosion rate of the weld metal is comparable to that obtained on wrought material.

Gas Welding

The austenitic chromium-nickel steels can be welded successfully by the oxy-acetylene process. Air-acetylene and oxy-hydrogen welding are not used because of the lower flame temperatures, consequent slow rate of welding and increased likelihood of carbide precipitation.

As in arc welding, an important factor is control of expansion and contraction by the use of suitable jigs, fixtures and chill plates as well as the use of tack welding and careful preheating. Suitable joint design facilitates this control and helps to avoid warping (see Figs. 10 and 11).

Stainless steel sheet, especially less than 0.04 in. (20 gage) in thickness, is usually flanged so that the length turned up is equal to the thickness of the sheet and the joint is welded without filler metal. Metal up to $^1/_{16}$-in. (16 gage) thick can be satisfactorily welded with a square butt type joint, while a single-vee groove joint is preferred for metal between $^1/_{16}$- and $^1/_4$-in. thick. Above

1/4-in. thick a double-vee groove joint is preferred.

In sheets 14 gage and heavier a root opening equal to the thickness of the sheet is used. In sheet of 16 to 20 gage, zero root opening is used.

Unless highly polished, the stainless steel surfaces to be welded should be cleaned with fine sandpaper, stainless steel wool, wire brushes or other abrasive. It is important that the materials used for cleaning be free of other metals, particularly iron and mild steel.

treme cases causing it to become brittle.

Uniformity in welding speed is essential, the forehand method being preferred on light-gage sheet, while backhand welding on heavier gages is sometimes preferred when speed is important. Complete penetration should be obtained in one pass without puddling or retracing the weld. If, however, it is necessary to stop or to work over a weld, this should not be done until the weld has entirely cooled.

Oxides formed during the welding of

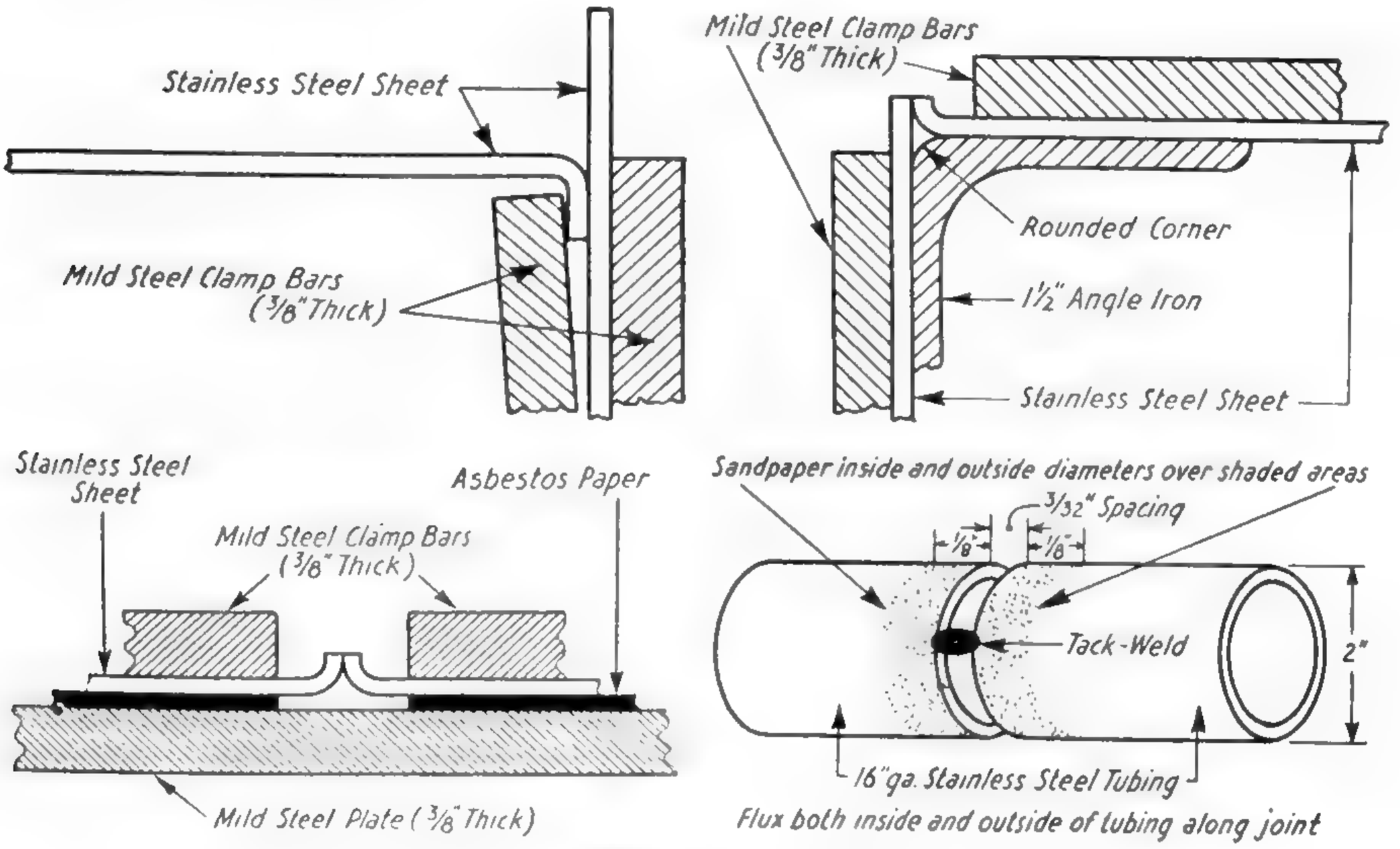


Fig. 11.—Clamping Methods for Oxy-Acetylene Welding

The welding tip should be one or two sizes smaller than that used for ordinary steel, with the oxy-acetylene flame just slightly reducing. An oxidizing flame should be avoided. With correct adjustment the excess acetylene feather will not project more than 1/16 in. beyond the tip of the inner cone, as seen through welding goggles.

The flame is generally held at an angle of 80 deg. to the surface of the stainless steel, with the tip of the inner cone almost, but not quite, touching the molten metal.

A flame with excess oxygen oxidizes chromium and contributes to porosity in the weld metal. Too reducing a flame contains carburizing gases which transfer carbon to the weld metal, injuring its corrosion resistance and in ex-

stainless steel must be dissolved by special fluxes designed for these alloys. These fluxes are usually available in the form of a dry powder which is mixed with water before use and applied with a small brush to cover all surfaces cleaned for joining. With experience this fluxing may be limited to the back side of the weld or to a thin layer on the welding rod.

Pressure Gas Welding.—Pressure gas welding is being used on austenitic stainless steels. Considerable care and attention are required to make satisfactory joints. As described in Chapter 7, a pressure gas weld is made without the use of molten metal in the weld joint. Generally speaking, any of the stainless steel grades may be welded. Because of the relatively low rates of heating and

cooling, consideration must be given to intergranular carbide precipitation in unstabilized austenitic chromium-nickel grades.

The kind of joint which lends itself best to pressure gas welding is the end-to-end or butt-type joint, used with simple sections like rounds, squares and heavy wall tubing. Joints in stainless steel to be pressure gas welded should be prepared by machining and grinding to make a precision butt fit. The faying surfaces must be held in intimate contact throughout the early heating stages to prevent the formation of an excessive amount of scale and oxide in the joint, which are difficult to disperse in these alloys.

The pressure used to insure intimate contact, to disperse the oxide film in the joint and to secure sufficient upset is generally higher than for ordinary steels because stainless steels have greater strength at elevated temperatures. The pressure must be applied uniformly to avoid partial separation of the abutting surfaces because heavy scaling would take place in those areas where the atmosphere entered. Close temperature control must be exercised because austenitic stainless steels have low thermal conductivity. Too fast a rate of heat input may overheat the surface and underheat the core, while a very slow heat input may cause excessive scaling.

A typical procedure for pressure welding Type 302 material would be to: (1) apply 10,000 psi. initial pressure; (2) heat to 2200°F. taking care that a small amount of upset occurs at about 1300°F. to help seal the joint against penetration by the gaseous atmosphere; (3) when the joint is uniformly heated, apply additional pressure to obtain sufficient upset and the desired length; and (4) allow to cool. Final annealing after welding is required to redissolve carbides precipitated during welding.

The upsetting is a necessary part of the operation because some scaling will invariably occur at the extreme outer edge of the joint and prevent bonding. This unwelded notch at the surface should be removed when the upset portion is machined off. Welded joints made under optimum conditions display strength and ductility equal to that of unwelded material. The notch-bar impact strength and fatigue strength are reported to be slightly lower than for unwelded material, and are the first mechanical properties to be affected by improper welding practice.

Customary practice usually involves the making of several sample welds which are subjected to a rigorous inspection, including tests for mechanical properties, macro etch tests for unbonded edges and microscopic examination of the structure at the weld interface. The final joints are subjected to non-destructive tests such as surface pickling, radiographic inspection and examination with supersonic devices.

Resistance Welding

General.—The austenitic stainless steels may be welded by any of the resistance welding processes described in Chapters 16 and 17. In fact, weld joints of high strength may be produced in the austenitic stainless steels with less difficulty than in most carbon and low-alloy steels. However, close control of welding variables must be exercised to safeguard the corrosion resistance of the joint.

In spot and seam welding of stainless steels the facts to be remembered are that due to the higher electrical resistance of chromium-nickel alloys, the welding currents used are, in general, lower than those used for the welding of mild steel. Also, the pressures are consistently higher, first, because of the higher contact resistance and, second, because of the greater strength, particularly at elevated temperatures.

The lower heat conductivity of stainless steels produces a thermal gradient in the weld which is considerably steeper than in mild steel welds, with the result that the quality of the weld is more susceptible to variations in the welding conditions, such as magnitude and time of the welding current, welding pressure and electrode shape. This condition is further aggravated by the comparatively short welding times necessary because of the danger of carbide precipitation as explained later.

A characteristic of austenitic stainless steels which proves an advantage in spot or seam welding is their low magnetic permeability. As larger masses of material enter the throat of the machine, it is not necessary to increase the welding current to compensate for changes in reactance, as is commonly done in welding strongly magnetic steels.

Spot Welding.—Successful spot weld-

ing of chromium-nickel alloys requires the following:

1. The welding current must remain the same at each weld and random transients cannot be tolerated. In addition, it is preferable that the welding current be as nearly sinusoidal as possible. The welding current should be applied synchronously, that is, always on the same point of the voltage wave, preferably the one which would not result in any transient current. The voltage variation at the welding transformer should not be more than 5%. The use of autotransformers between the welding transformer and the welding contactor should be avoided.

2. The duration of the welding current should be kept constant. Welding at time intervals of less than 5 cycles ($^1/_{12}$ of a second) should not be attempted unless timing accuracy of better than $^1/_4$ of a cycle ($^1/_{240}$ of a second) can be assured. Whenever it is desirable to use very short time intervals as in the case of welding very thin gages, timing equipment of the full electronic type, independent of mechanical switching of current, should be used. A timing variation of more than 1 cycle ($^1/_{60}$ of a second) in the duration of the weld should not be tolerated in any case.

3. The welding pressure must be as uniform as possible. Variation in pressure will affect both the current density of the weld (by changing the contact area) and the electrical resistance of the weld. For this reason, adequate jigs must be provided to hold the surfaces to be welded in good contact with each other and relieve the welding arms from the need of flattening out ripples and buckles.

4. The surfaces to be welded must be thoroughly cleaned and completely free from all scale, oxide, dirt, grease or drawing compound.

5. Considerably higher pressure should be used than is customary with mild steel. Very good results can be obtained with pressures two to three times those used on mild steel.

6. For best results the electrode tips should be made of special high conductivity copper alloys possessing not less than 70 Rockwell B hardness, nor less than 85% electrical conductivity. They should be internally cooled to promote rapid cooling of the weld and minimize carbide precipitation.

7. Proper pressure should be maintained at all times. Insufficient pressure causes blow-holes inside the weld metal and, in extreme cases, actual surface fusion of the metal.

8. Because of the comparatively high contact resistance of high-tensile austenitic steels, the short-circuiting effect of the preceding welds on each new weld may be considerable, particularly if more than three metal thicknesses are welded together at a time and if the spacing of spot welds is comparatively close. This effect should be measured and compensated for by a suitable increase of the welding current.

It has been established that with appropriate technique it is feasible to spot weld the high carbon (0.15% C max.) unstabilized material without harmful carbide precipitation and without undesirable loss of ductility.

For the thinner gages there is usually little difficulty in keeping the welding time below the danger point of harmful carbide precipitation, but in the thicker material the welding times and currents must be held more closely within specified limits. When the thickness is much greater than $^1/_8$ in., the higher carbon alloys, Types 301 and 302, may show undesirable carbide precipitation. Thus, if a structure made of thicker material is to be subjected to a corrosive exposure, it is advisable to employ either the low carbon Type 304 steel or stabilized alloys according to the degree of corrosive exposure.

Because the weld nugget is normally subject to rapid cooling, equivalent to quenching, spot welds in austenitic stainless steels are extremely tough and ductile. It is possible to secure high joint efficiencies.

Spot welding is particularly adapted to the fabrication of light weight structures from high-strength Type 301 and Type 302 stainless steels which can be obtained with tensile strengths in excess of 150,000 psi.

The weld time used for high-tensile stainless steel is of great importance if harmful carbide precipitation is to be avoided. In general, the welding time must be of comparatively brief duration and must be accurately controlled.

In thin gage material a hold time of $^1/_{10}$ sec. following the cessation of current flow is recommended to assist in cooling the spot as quickly as possible below the carbide precipitation range. In heavier

gages this period should be extended. One-sixth of a second has been suggested for material $^1/_8$-in. thick.

Electrode tip dimensions affect the diameter and thickness of the weld nugget and under-sized tips will buckle and distort. Satisfactory welds for most purposes can be made by using the *Recommended Practice for Spot Welding Stainless Steel,* which is given in Chapter 16. However, in fabricating highly stressed structures, individual spot-weld strength values should be checked by the methods described in Chapter 42.

The appearance of spot welds made on austenitic chromium-nickel steels is usually very good. By delaying the release of the welding pressure until the weld has cooled below oxidizing temperature, complete freedom from discoloration can often be obtained. Where slight discoloration is present, it can easily be removed by cleaning with powdered pumice, by scrubbing with alkali cleansers or by brief immersion in a solution of 10% nitric acid plus 2% hydrofluoric acid at room temperature, or 50% hydrochloric acid at room temperature. The latter two solutions are corrosive and parts should not be exposed to them for long periods of time or the surface may become etched.

To reduce or minimize spot weld indentation or depressions, the use of an oversized flat tip on the exposed side and a dome-shaped tip on the back side has been recommended. Another method employs a shim of soft high-conductivity material like aluminum under the electrode tip on the exposed side.

The spot-weld cross section can be determined readily by cutting a sample weld through the middle and, after a sufficient polish, etching it in a hot solution of 20% nitric and 5% hydrofluoric acid. The weld nugget will stand out in clear outline and the quality and approximate strength of the weld can be easily determined by measuring its diameter and depth of penetration. This method has the advantage of showing up the presence of any blow-holes or cracks indicative of insufficient welding pressure.

The spacing of spot welds joining stiffeners to panels in reinforced panel designs is a function of the compressive load the panel is designed to carry without buckling between the spots.

The following formula (applicable only when weld is close to web of stiffener) can be used as a guide in determining the proper spot-weld spacing in terms of the buckling stress:

$$L = 1.8t\sqrt{\frac{E}{s} - \frac{E}{T.S.}}$$

where

L = weld spacing
t = metal thickness
s = design stress at which buckling will appear in thinnest metal
$T.S.$ = ultimate tensile strength of thinnest metal
E = Young's modulus of elasticity

The weld shear strength and to some extent the weld diameter should be used as a criterion for determining the exact welding condition. In addition, the weld metal should be free from blow-holes and porosity, though on metal 0.093 in. and thicker as well as on multilayer combinations exceeding $^3/_{16}$ in. in total thickness, a certain amount of porosity will be present unless extremely high pressures are used. It is generally agreed that in these cases a slight amount of porosity can be tolerated.

Frequently the geometry of the part welded is such that the pressures shown in the Recommended Practice cannot be used. To some extent the lowering of pressure can be compensated for by decrease of current and increase of time. Any appreciable decrease of pressure, however, will result in smaller, hence, weaker welds.

Distortion and Stresses Due to Spot-Welding Shrinkage.—The coefficient of expansion of the austenitic chrome-nickel steels is considerably higher than that of the mild or medium carbon steels. On the other hand, their thermal conductivity is much lower. Accordingly, it is to be expected that the distortion and stresses due to the actual welding shrinkage will be more severe. The distortion, buckling and warping due to the shrinkage of spot or seam welds present a difficult problem in the welding and fabrication of stainless steels. In welding austenitic chromium-nickel structures a study of the effects of shrinkage on the completed structure should be considered so that suitable provisions may be included in the design.

In spot welding, the extent of welding shrinkage can be greatly reduced by keeping down the size of the individual

welds. There is a definite relationship between the stiffness of the sheets being welded and the amount of welding shrinkage within each individual spot which can exist without distorting the sheets. This relationship will vary, depending on the tensile characteristics of the sheets, but in general it will be found that the safe upper limit of spot-weld diameter is four to five times the thickness of the thinnest sheet welded. For this reason, from the point of view of shrinkage, more spots of small diameter are to be preferred to few spots of large diameter even if the total volume of weld metal is the same in both cases.

The distortion and warping produced by welding shrinkage can be overcome to a certain extent by peening or trip-hammering the weld metal. As a rule, it will be found helpful if all spot and seam welds are thoroughly trip-hammered, preferably one row at a time, at the end of each operation and before another welding operation is attempted.

Seam Welding.—Much use is made of roll spot and seam welding in joining austenitic stainless steel sheet and strip. For a detailed description of this process refer to Chapter 16, which includes the *Recommended Practice for Seam Welding Stainless Steel.*

Projection Welding.—Projection welding is essentially a technique for securing localized contact by means of projections or embossments on one or both of the surfaces to be joined. The size and shape of the projections may be varied at will. The *Recommended Practice for Projection Welding Stainless Steel* is included in Chapter 16.

Projection welding is widely used in the fabrication of stainless steel wire into refrigerator shelves, stove grates, cooker baskets, heater guards and many other wire products. Two distinct types of joints are used: lap joints, which involve line contact between the wires to be welded, and cross-wire joints, in which the wires make point contact. The latter generally proves to be more satisfactory from the standpoints of strength and appearance. Cut and formed wires are usually held in frames or jigs for the welding operation. The welds may be made singly using conventional flat-face tips, or tips in which a vee groove has been cut in the face to provide additional contact area on the wire. For rapid production, large flat bar-type electrodes may be employed to make multiple welds. As many as forty or more cross-wire joints may be welded at one time.

The most satisfactory welds are made on stainless steel wire using short welding times, in the range of 1 to 5 cycles of 60-cycle current, and commensurate amperage. The pressure or electrode force is somewhat lower than used in spot welding sheet to avoid excessive deformation of the wire sections. Short welding times also minimize discoloration which appears around the welded joint.

Flash and Upset Welding.—A description of these two processes is given in Chapter 17. In the case of stainless steels the current requirements are about 15% less than for mild steel and the upsetting pressures range from 13,000 to 25,000 psi. of weld area, which are somewhat higher than for mild steel. Because of the higher contact resistance and the greater upsetting forces, the clamping pressures on stainless steel must be 40 to 50% higher than employed on mild steel.

The flash-welding process has several inherent advantages over the upset welding process for stainless steel. A sound joint is made in either case by exerting sufficient pressure to close up all voids in the weld zone and to extrude all metal in the molten state along with slag or other impurities. In an upset weld, a very large and often objectionable upset is welded to insure a clean joint. In a flash weld, however, the oxides are largely forced out along with the small amount of plastic metal that forms in the joint, and the deformation of the section is smaller. Flash welding is faster and more economical in power consumption as it requires the generation of less heat.

Brazing

Stainless steels can be brazed when welding is impracticable, using a silver brazing alloy. Silver brazing alloys are resistant to many types of corrosion and have been used to join stainless steels to plain steel, copper and other alloys. The selection of a brazing alloy with a low melting point, around 1200°F., is recommended to minimize the heat-affected zone in the base metal. Borax or boric acid fluxes used in high-temperature brazing are not suitable with silver alloy brazing (see Chapter 22).

Brazing stainless steels with high melt-

ing point bronze rods is not recommended because of the likelihood of serious embrittlement caused by intergranular penetration of the brazing alloy into the base metal.

After cleaning the areas to be brazed, flux in paste form is applied. The silver alloy wire or strip is fitted over the joint and an oxy-acetylene torch, adjusted to a slightly reducing flame, is applied, playing the flame back and forth. Gas and electric furnaces with neutral atmospheres can be used for production work.

After brazing all remaining flux should be completely removed with a high-pressure steam jet or hot water.

Mechanical Properties of Welded Joints.—Data selected from some of the references in the bibliography of this chapter on the mechanical properties of joints welded by various processes are given in Table 9.

Soft Soldering

Soft soldering of austenitic stainless steels will give joints with good adhesion.

Table 9—Mechanical Properties of Joints Made by Various Processes

A. Tensile Properties of Arc-Welded Type 321 (18–8 Ti) from 75 to 1610°F.

Temperature, °F.	Tensile Strength, Psi.	Tensile Strength, % of Unwelded	Elongation in 2 In., %	Elongation in 2 In., % of Unwelded	Reduction of Area, %	Reduction of Area, % of Unwelded
75	79,000	98	59	76	74	100
520	59,000	98	32	71	62	94
930	50,000	93	31	76	65	99
1420	19,000	>100	27	..	61	>100
1610	12,000	...	16	..	55	...

Notes: Double-vee groove welds in 3/4-in. plate with E308 electrode. Welds quenched from 1950°F. before machining standard 0.505-in. diam. specimens. All fractures in base metal.

B. Endurance Limit of Oxy-Acetylene Butt-Welded Type 304 (18–8) Tubes

Heat Treatment	Tensile Strength Welded Tube,[a] Psi.	Endurance Limit: Unwelded Tube, Psi.	Endurance Limit: Welded Tube,[b] Psi.	Ratio of Welded to Unwelded Tube
As-welded	85,000	24,000	16,000	0.67
1/2 hr., 1990°F.	81,000	....	16,000	..

[a] Based on cross-section of unwelded tube.
[b] Unmachined oxy-acetylene butt-welded tubes 1-in. O.D., 1/16-in. wall, using Type 304 (18–8) welding rods; rotating beam test.

C. Tensile Properties of Pressure Gas Welded Joints of Type 347 (18–8 Cb), Type 321 (18–8Ti) and Type 310 (25–20) Steels

Steel Type	Condition	Tensile Strength, Psi.	Yield Strength, Psi.	Elongation in 2 In., %	Reduction of Area, %
347	Welded	77,000	44,000	39	61
	Welded and forged	88,000	51,000	55	68
	Unwelded	88,000	48,000	57	59
321	Welded—not forged	78,000	45,000	40	45
	Unwelded	83,000	46,000	61	75
310	Welded—not forged	75,000	40,000	46	52
	Unwelded	75,000	42,000	51	50

Notes: Oxy-acetylene flame used as a source of heat, and pressures from 3000 to 6000 psi. at 2200°F. except as noted. The tensile specimens were 0.505-in. diam., 2-in gage length.

D. Tensile Strength of Seam Welded and Shielded Metal-Arc Welded Joints of Type 302 (18–8) and Type 347 (18–8 Cb) Sheet at Room Temperature and −320°F.

Steel Type and Condition (0.026-In. Sheet)	Type of Weld	Room Temperature: Tensile Strength, Psi.	Room Temperature: Joint Efficiency,[a] %	−320°F.: Tensile Strength, Psi.	−320°F.: Joint Efficiency,[a] %
302 (1/2 hard)	Unwelded	169,000	..	275,000	...
302 (1/2 hard)	Seam weld	149,000	88	175,000	63
347 (Annealed)	Unwelded	96,000	..	232,000	...
347 (Annealed)	Seam weld	93,000	97	233,000	100
347 (Annealed)	Arc weld	93,000	97	190,000[b]	82

[a] Joint efficiency—Ratio of tensile strength of weld to tensile strength of unwelded specimen at test temperature.
[b] Broke in weld.

A solder containing at least 50% tin is recommended. The joint surface must be thoroughly cleaned of grease or other oils and unless pickled surfaces are used, it must be roughened by filing, rubbing with emery cloth, grinding or by etching with commercial hydrochloric acid. Etching requires only a few minutes and the acid should be thoroughly removed after use (see Chapter 23).

More active fluxes than used for mild steel are required to cut through the chromium oxide film present on stainless steel and permit good adhesion of the solder. Orthophosphoric acid is a satisfactory flux.

The use of a large, hot soldering iron which will quickly flow the solder into the joint is recommended. Prior tinning of the edges is helpful and will assist in keeping them clean before final soldering.

such devices as the use of extreme preheat, auxiliary heat, a waster strip of plain-carbon steel placed over the cut or the use of a plain-carbon steel rod introduced between the tip of the torch and the work.

Both the oxygen-cutting and arc-cutting processes, now available, will produce a heat-affected zone in the base metal next to the cut. The stabilized alloys are unaffected but other grades may require annealing treatment to restore full corrosion resistance to the material. If used as a means of edge preparation for subsequent welding, removal of the adhering oxide film from the cut face by light grinding is usually recommended. In this case the heat effects from welding will determine largely whether final treatment of the weldment is required.

Oxygen Cutting.—Two methods of oxygen cutting are now available for use with

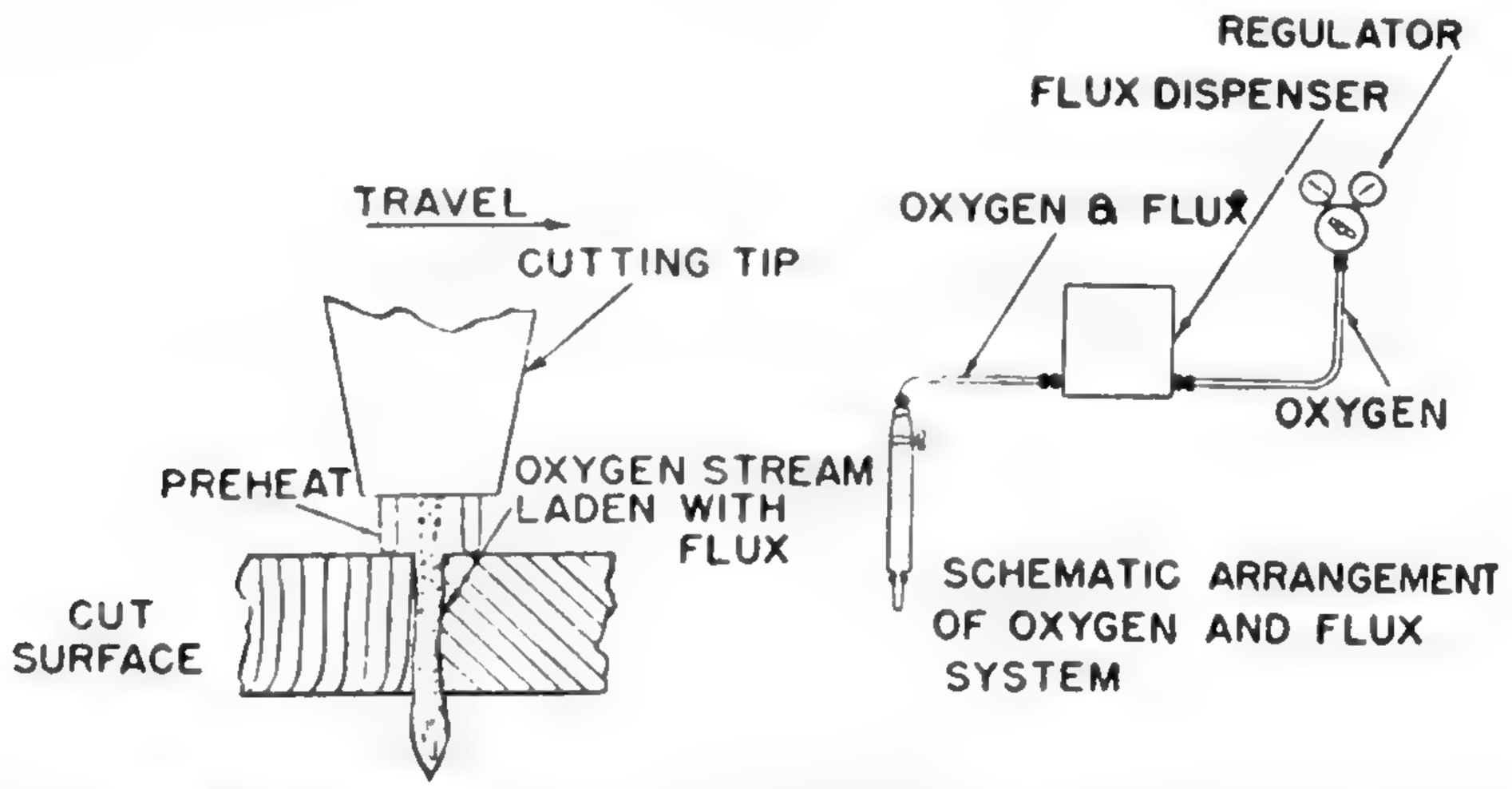


Fig. 12.—Schematic Diagram Showing the Principles of the Flux Injection Cutting Process

Because relatively strong acid fluxes are necessary for good results, it is essential that the excess be thoroughly removed after soldering; otherwise, they may eventually discolor and pit the surface of the steel. Washing or scrubbing with ammonia water or a solution of laundry soap and washing soda, followed by thorough rinsing, is desirable.

Cutting Processes

The tendency for molten stainless steel to become covered with a refractory film of oxidation products has prevented the successful cutting of these alloys by conventional oxygen-cutting processes. Prior to the introduction of the methods described below, cutting was achieved by

stainless steels which are both versatile and economical. All the common alloys can be satisfactorily cut in all thicknesses by these processes. The resultant cut surfaces are smooth and straight, comparing favorably with the results obtained with carbon steel. Manual cutting, machine cutting, stack cutting and intricate shape cutting are possible. The techniques are similar to those used in cutting carbon steels as described in Chapter 24.

One method, the flux injection procedure (see Fig. 12), introduces a chemical powder or flux with the oxygen stream. This process depends upon the fluxing action of the powder on the refractory compounds formed by the oxidation of the alloy.

The other method, powder cutting (see Fig. 13), introduces an iron-rich powder into the reaction zones. This metallic adjuvant is exothermic in its reaction and provides the additional heat required for melting and fluxing away the refractory oxides.

For a more complete description of these two methods, see Chapter 24—Oxygen Cutting.

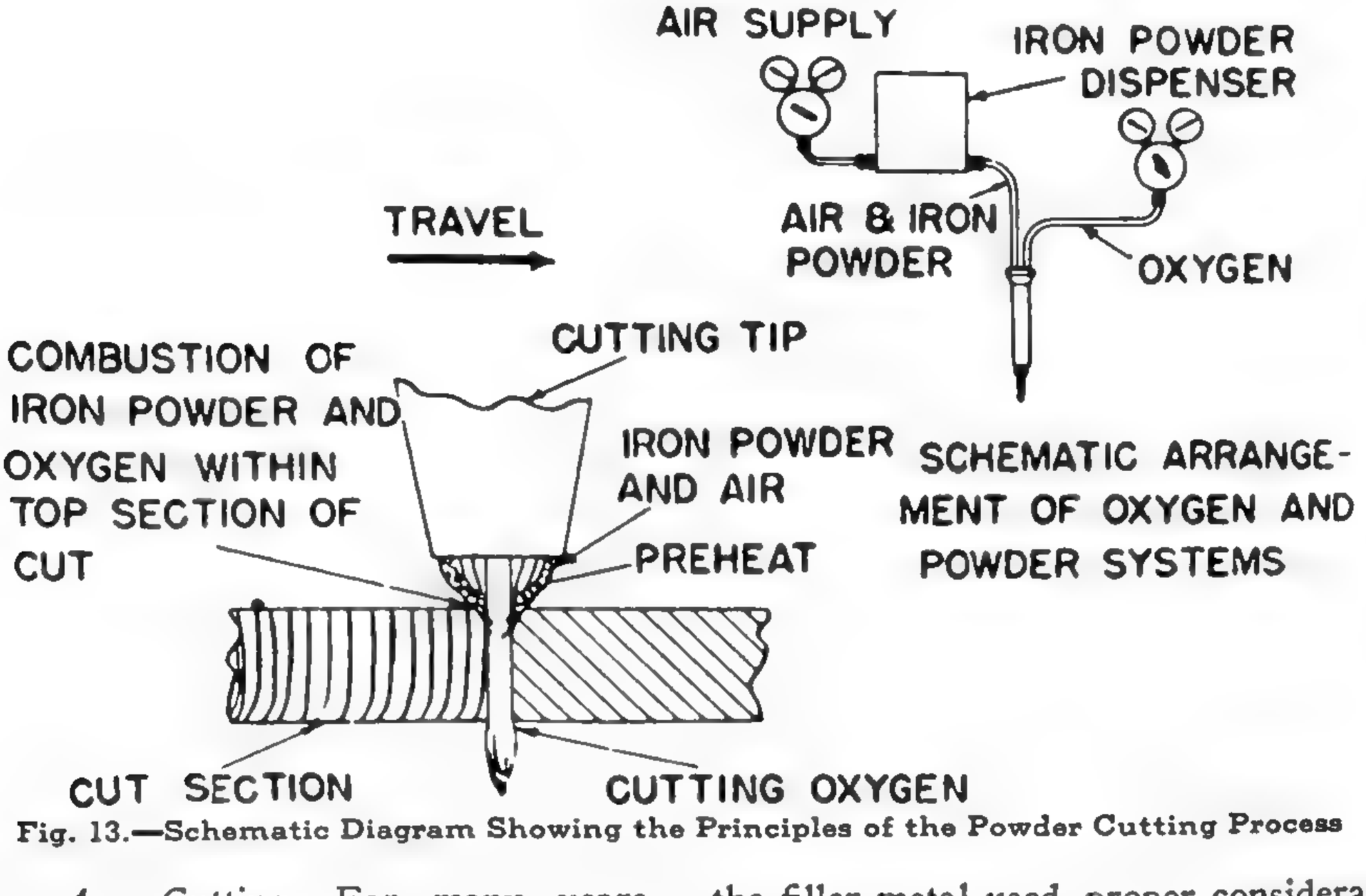


Fig. 13.—Schematic Diagram Showing the Principles of the Powder Cutting Process

Oxy-Arc Cutting.—For many years, stainless steels have been severed by means of the carbon-arc or a metal-arc electrode (usually an E6020 type, mild steel) without oxygen. High currents are employed and the action is slow thus causing a large amount of heat to accumulate in the piece being cut. The cut is generally very rough and requiries considerable dressing.

By employing a tubular mild steel rod coated in a manner similar to a welding electrode, it is possible to introduce oxygen into the center of the arc resulting in substantial increase in cutting speed. The oxy-arc process combines the heat of the electric arc with the heat of combustion of the electrode core. Fluxing of the refractory chromium oxides is accomplished by the iron oxide formed from the core and the silicates of the coating (see Fig. 14).

Further details on the above cutting processes can be found in Chapters 24 and 25 and in some of the references contained in the bibliography.

Joining Austenitic Stainless Steels to Carbon and Low-Alloy Steels

The welding of the austenitic stainless steels to carbon, low-alloy and straight chromium steels, that is, ferritic steels, can be readily accomplished by any of the accepted welding processes. Because the weld produced is of necessity a composite mixture of the two base materials and of the filler metal used, proper consideration must be given to prevent the formation of an air-hardening and brittle weld which would crack upon cooling. The best preventive of this brittle condition is the use of a welding rod or electrode, sufficiently high in alloy content to produce a weld having austenitic characteristics after dilution by the mild steel. The most widely used material for such welding is either Type 309 (25–12) or Type 310 (25–20), the welding technique being the same as that used for any of the accepted welding processes and the same rules for fit-up, electrode sizes and current values being applicable.

The selection of the best filler metal for welding dissimilar metals may be predicted by referring to the phase diagram shown in Fig. 8.

A weld of dissimilar metals involving low-carbon weld metal and high-carbon base metal may show evidence of carbon diffusion if the weld is subjected to elevated temperatures either as a postheat treatment or in service. Carbon has been

observed to diffuse into austenitic welds from carbon-molybdenum steel base metal operating for long periods of time at 900°F. This may occur even in cases where there is the same initial carbon content in both weld and base metal. Much more rapid diffusion occurs as the temperature increases: at 1600°F. heat treatments for as little as 1 hr. have shown evidence of diffusion. Whether or not carbon diffusion is detrimental will depend upon the effect of decreased carbon in the base metal and of increased carbon in the weld metal on the properties of the materials in service.

COMMON APPLICATIONS

The austenitic stainless steels are well adapted to fabrication by nearly every type of welding. As a result it is common to find weldments in every field of application of these alloys. Numerous examples are present in the fields of aircraft, food processing equipment, chemical processing equipment, oil refining equipment and so on. The selection of the proper grade of stainless steel and the best method of welding for a particular application should be discussed with the supplier.

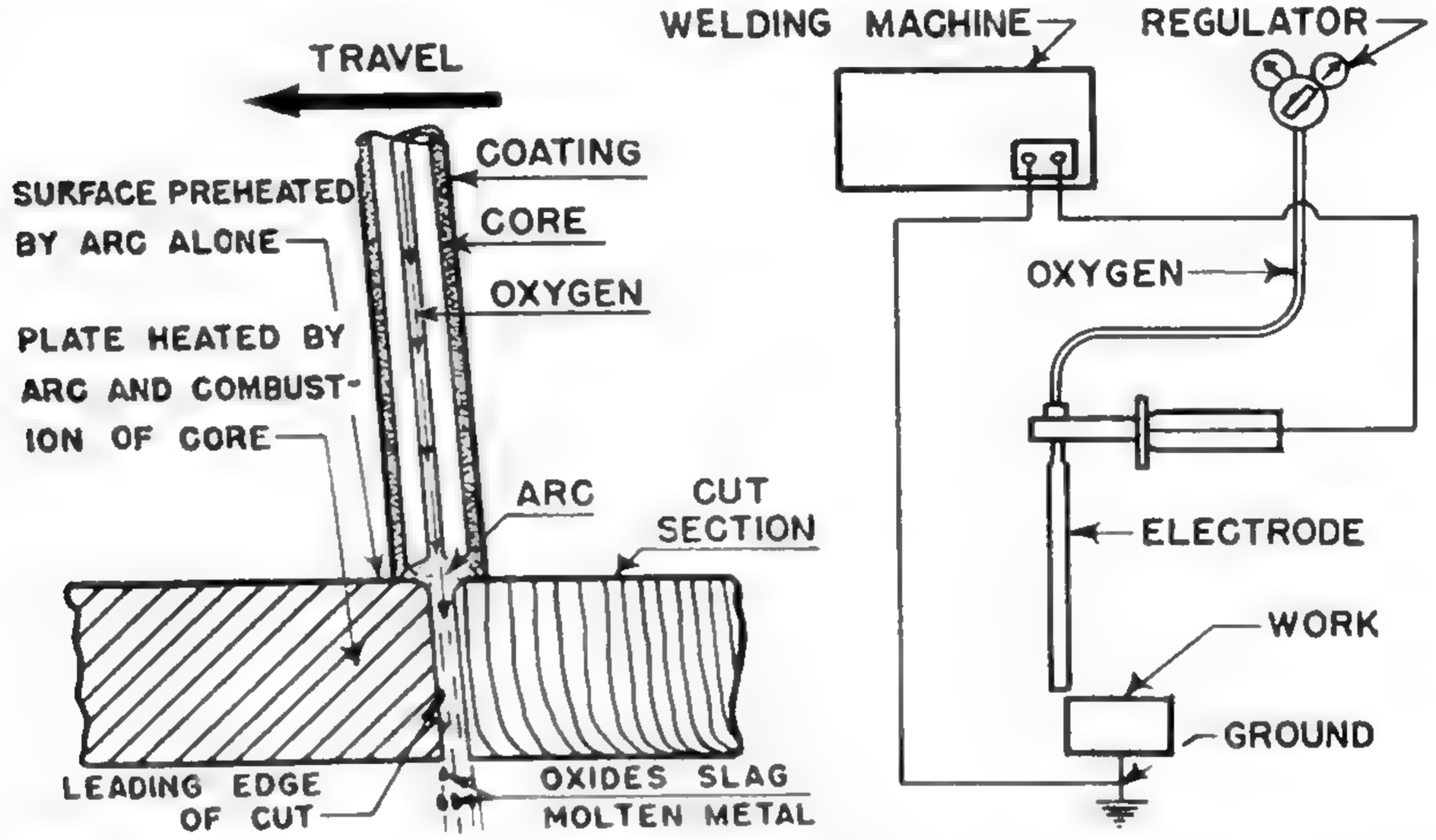


Fig. 14.—Schematic Diagram Showing the Principles of the Oxy-Arc Cutting Process

BIBLIOGRAPHY

1. *Welding of Aircraft Structures,* J. B. Johnson, The Welding Journal, September 1936.

2. *The Stress-Strain Characteristics of Cold-Rolled Austenitic Stainless Steels in Compression as Determined by the Cylinder Test Method,* R. Franks and W. O Binder, Proceedings, American Society for Testing Materials, 1941.

3. *High-Temperature Tensile Tests of Welded 18 8,* O. H. Henry and A. L. Huber, The Welding Journal Res. Suppl., March 1941.

4. *Comparison of the Properties of 18 8 Weld Metal, Cast Metal and Rolled Metal,* K. W. Ostrom and R. D. Thomas, Jr., The Welding Journal Res. Suppl., July 1941.

5. *Tensile and Compressive Properties of Some Stainless Steel Sheets,* C. S. Aitchison, W. Ramberg, L. B. Tuckerman and H. L. Whittemore, National Bureau of Standards Journal of Research, April 1942.

6. *Cold-Rolled Stainless Steels in Aircraft,* R. Franks and W. O. Binder, Mechanical Engineering, August 1942.

7. *Stainless and Heat-Resisting Steels,* Steel Products Manual, American Iron and Steel Institute, May 1946 (Rev. February 1949).

8. *Properties of Various Alloys at Sub-Zero Temperatures,* A report of North American Aviation, Inc., Iron Age, November 14, 1946.

9. *Pressure Welding Stainless Steel Rings,* C. J. Burch and A. L. Rustay, Steel, January 13, 1947

10. *New Oxygen-Arc Process for Cutting Ferrous and Non-Ferrous Alloys,* H. R. Clauser, Materials and Methods, January 1947.

11. *Pressure-Welding Stainless Steel Rings,* A. L. Rustay, A. Crowell, S. M. Jablonski, C. J. Burch, The Welding Journal, February 1947.

12 *Inert-Gas Shielded Arc Welding for Difficult-to-Weld Materials,* H. R. Clauser, Materials and Methods, April 1947.

13. *The Inert-Gas Shielded-Arc Welding Process,* G. L. Gibson, The Welding Journal Res. Suppl., May 1947.

14. *Stainless Steel Cutting,* H. Hughey, The Welding Journal, May 1947.

15. *Selection of Austenitic Electrodes for Welding Dissimilar Metals,* A. L. Schaeffler, The Welding Journal Res. Suppl., October 1947.

16. *The Use of Flux-Injection Cutting for Stainless Steels,* G. E. Bellew, The Welding Journal, February 1948.

17. *Powder Cutting as a Production Tool,* D. H. Fleming, The Welding Journal, March 1948.

18. *Symposium on Evaluation Tests for Stainless Steels,* American Society for Testing Materials, June 1949.

CHAPTER 31B

AUSTENITIC MANGANESE STEEL*

GENERAL PROPERTIES

AUSTENITIC MANGANESE steel, which is also called *Hadfield's manganese steel* after its inventor, is an extremely tough nonmagnetic alloy in which the usual hardening transformation occurring in carbon and low-alloy steels has been suppressed by a combination of high manganese content and rapid cooling from a high temperature. It is characterized by high strength, high ductility and excellent wear resistance. In the form of castings or of rolled shapes it serves many industrial requirements as an outstanding material for resisting severe service that combines abrasion and heavy impact.

Composition

The nominal composition of austenitic manganese steel includes 1.2% carbon and 12 or 13% manganese as essential elements. Commercial analyses will usually vary within the 1.0–1.4% C and 10–14% Mn ranges established by ASTM *Specifications for Austenitic Manganese-Steel Castings* (Serial Designation A128) and some other specifications. There is a tendency to keep the chemistry to the mid-point of the carbon range and at 12–13% Mn as the lower limit is associated with somewhat inferior tensile properties and the upper limit provides no economic advantage.

Carbon has a slight but distinct effect on yield strength, both decreasing together. Its effect on other tensile properties is overshadowed by variables such as grain size, but there is an indication of an optimum around 1.15%. A higher carbon content may cause trouble in heat treatment or in foundry handling. Low carbon is helpful in avoiding the embrittling effect of carbide precipitation on cooling below the limit of solubility and for this reason is generally employed in welding rod alloys and other modifications where the normal heat treatment involving a water quench is impracticable.

Manganese contributes a vital austenite-stabilizing effect, delaying transformation by producing sluggishness, rather than eliminating it. Thus, with a simple steel containing 1.1% manganese, quenched from above 1600°F., the beginning of the hardening transformation at 700°F. may occur in about 15 sec. while, with 13% manganese, about 2 days may be required. Below 500°F., phase change and carbide precipitation are so sluggish that for practical purposes they may be neglected in the absence of deformation if the manganese content is above 10%.

Manganese within the limits 10–14% has almost no effect on yield strength but it does benefit ultimate tensile strength and ductility. The difference between 10 and 13% manganese can be demonstrated, though it requires careful control of other variables to make it apparent. Below 10% Mn the tensile properties decline rapidly, falling to perhaps one-half their normal level at about 8% Mn.

A lower limit of 11% Mn is desirable for critical requirements, though the improvement over 10% is slight. The upper limit is rather arbitrary and is probably more dependent on alloy cost than on results, as acceptable properties may be produced up to at least 20% Mn.

Silicon is included chiefly for steelmaking purposes. While it infrequently exceeds 1% it may be employed up to about 2% to produce a moderate increase in yield strength and resistance to plastic flow under repeated impact. At about

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* Prepared by a committee consisting of F. N. Stone, American Manganese Steel Div., American Brake Shoe Co., *Chairman;* H. S. Avery, Metallurgical Dept., American Brake Shoe Co.; H. A. Fabert, Jr., W. A. George, E. M. Kaulbach and H. D. Sweeney, all of American Manganese Steel Div., American Brake Shoe Co.

2.2% a sharp reduction in strength and ductility begins, rendering the range above 2.3% Si practically worthless for normal applications.

opinion is based on room temperature mechanical properties. Above 0.06% it reduces hot strength and ductility. This tendency is related to the formation of

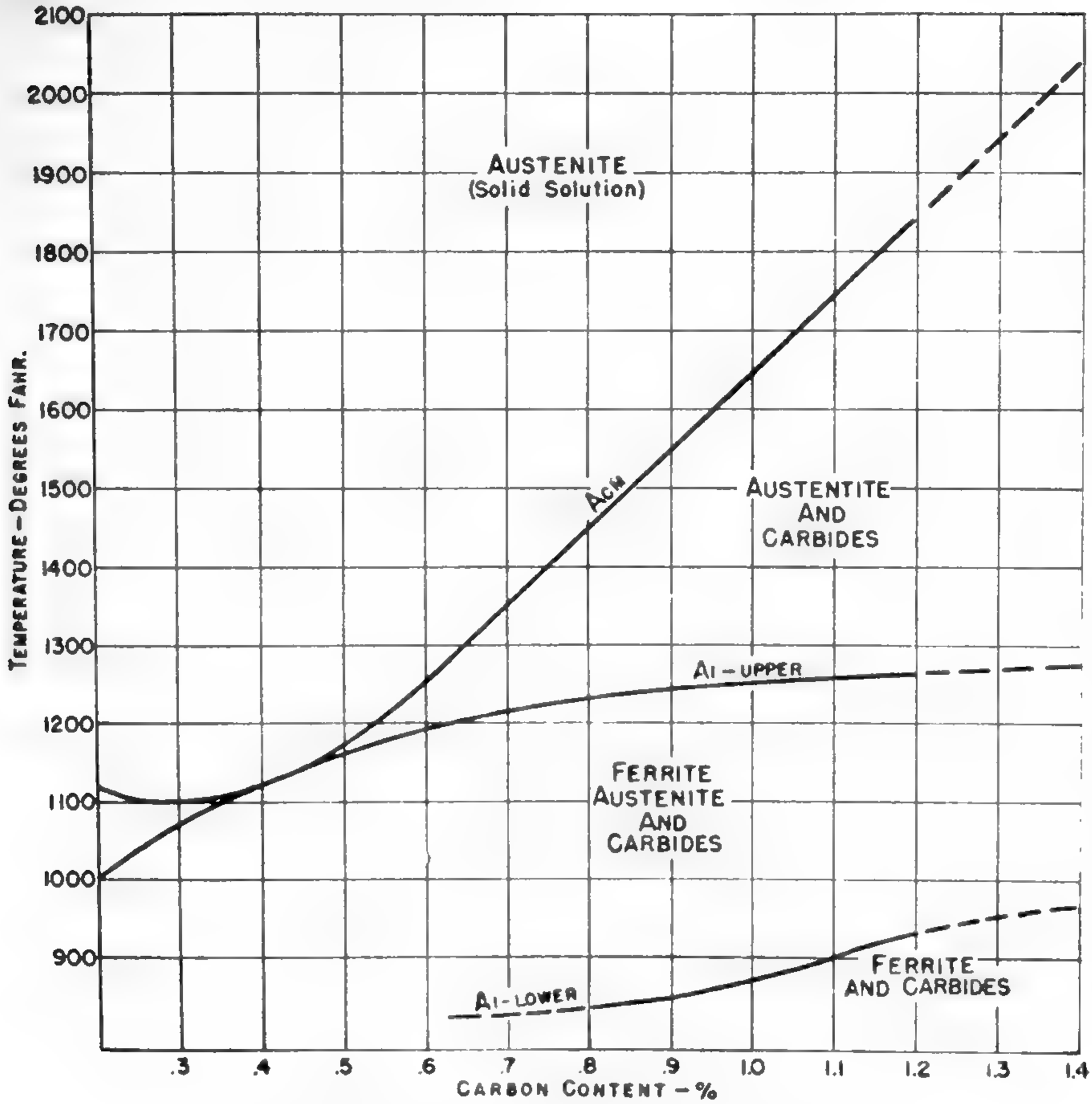


Fig. 1.—Effect of Heat Treatment on 12.5% Mn Steel

Structures retained at room temperature by water quenching.

Sulfur is seldom a factor in 13% manganese steel, the scavenging effect of manganese, for which it is customarily added in simple steels, operating to eliminate sulfur by slagging or fixing in the form of innocuous rounded inclusions of manganese sulfide. Elongation of these in wrought steel may contribute to directional properties; in cast steel they are considered harmless.

Phosphorus is generally reputed to be harmless below 0.10%. However, this hot cracks in castings, contributing to the production problems of the foundry. However, unless cracked castings escape inspection and go into service, a phosphorous content of less than 0.10% is considered acceptable to the user.

Other elements, such as nickel, molybdenum, chromium, copper or vanadium, may be added to standard manganese steel to modify the usual properties, but most of the commercial product is unalloyed.

Heat Treatment

The as-cast or as-rolled structure of manganese steel contains carbides and other transformation products that produce marked brittleness by their continuity.

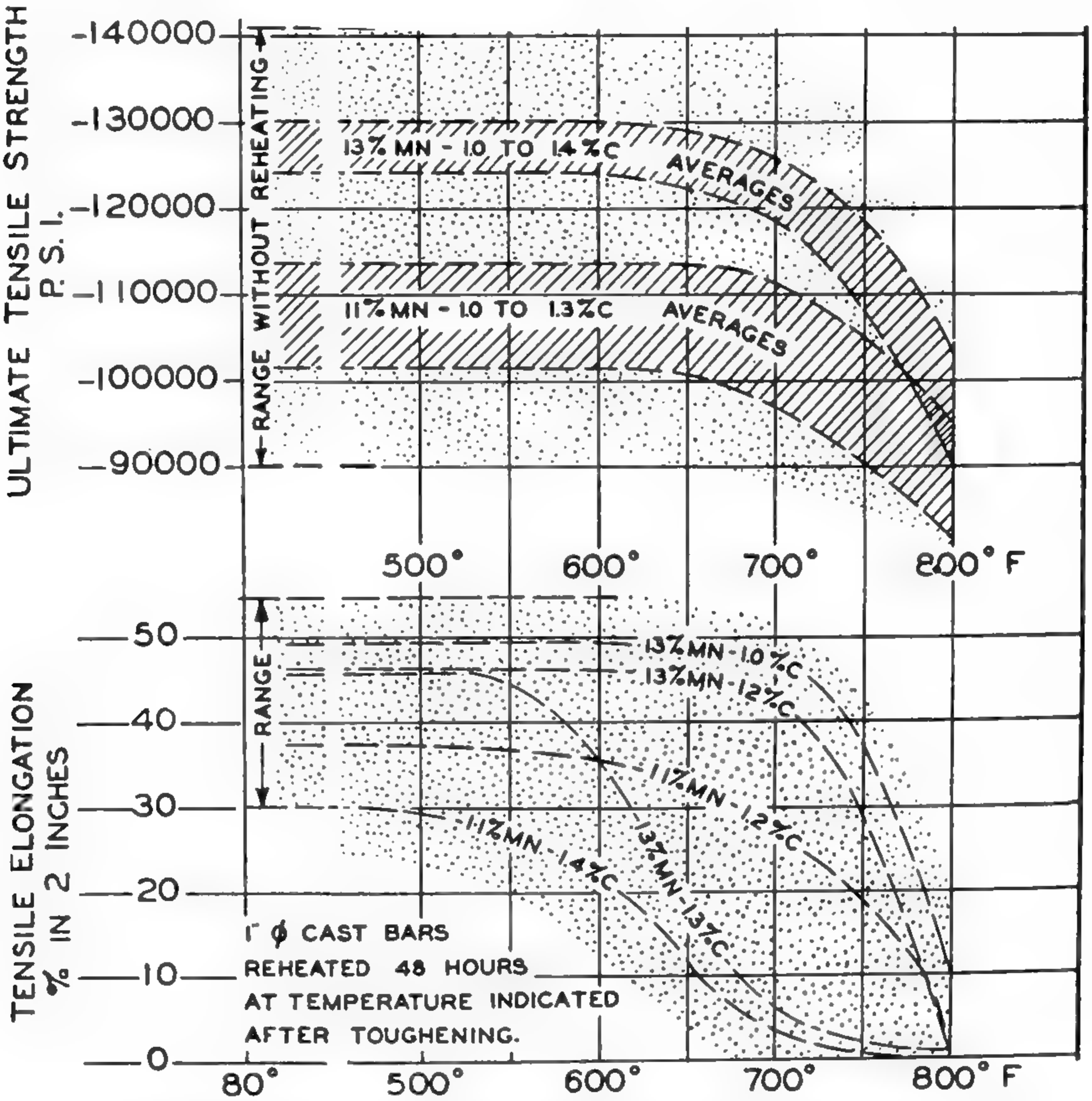


Fig. 2.—Embrittlement Produced by Reheating Austenitic Manganese Steel

The as-cast tensile strength (in small test castings) will approximate 60,000 to 70,000 psi. with elongation values down to less than 1% in 2 inches. The standard toughening heat treatment involves austenitizing and water quenching, producing the normally expected mechanical properties.

The austenitizing temperature should be high enough to insure complete solution of carbon, as indicated by Fig. 1. A long time at temperature is not considered necessary, as equilibrium is probably established within 20 to 30 min. at temperatures above 1850°F. An allowance for lag in heat transfer to the center of heavy sections is required, of course.

The speed of quenching is important, although difficult to accelerate beyond the rate fixed by heat absorption from a surface cooled by agitated water. The mechanical properties at the centers of heavy sections are characteristically lower because of slower quenching rates.

Internal stresses from quenching coupled with the lower properties of heavy sections have established a practical maximum of 5 or 6 in. for the thickness of commercial castings. Stresses also develop during mold cooling and thus are likely to produce cracks in heavy castings before heat treatment. However, while heavy sections are a greater problem in production they are an asset as a base for welding. The large mass of cold metal

quickly cools a welded area and tends to reduce possible damaging effects of the welding heat on austenitic steels.

The relatively high heat-treat temperature together with the high carbon content combine to cause marked surface decarburization and some loss of manganese. The skin thus may be partially martensitic (and magnetic) at times and usually is weaker than the underlying metal. Tensile deformation in service sometimes produces numerous cracks in this inferior skin, which terminate when the very tough austenite of normal composition is reached. Service performance is not seriously affected unless critical fatigue conditions of very light sections are involved.

Reheating

Reheating of austenitic manganese steel parts in the field is much more serious than for ordinary structural steels. Instead of the usual softening and increase of ductility, manganese steel will become embrittled if heated enough to induce partial transformation of the austenite. As a generalization, this alloy should never be heated above 500°F. either by accident or design, unless the standard toughening treatment is to be applied later. Though welding is an exception to this rule, it is tolerable only when the damaging effect is kept to the practical minimum.

Both time and temperature are involved, lower temperatures requiring longer for the impairment to develop. Composition also has an effect. Figure 2 is suggestive of the magnitude of the embrittlement. As large castings are sometimes mounted with a backing of molten zinc or lead, temperature should receive adequate attention in such cases. However, the most important complication from this behavior arises during welding. The embrittlement demonstrated in Fig. 2 (see also Fig. 8) for a 48-hr. heating period can develop between 1000 and 1600°F. during the time intervals associated with welding. The standard toughening heat treatment (water quenching from above 1800°F.) will remove embrittlement caused by reheating, but unfortunately it is seldom practical to do this in the field.

Physical and Mechanical Properties

The range of tensile properties produced in other alloy steels by heat treatment is developed approximately in manganese steel by work hardening. Manganese steel probably has no equal in its ability to work harden, exceeding even the austenitic stainless steels in this respect. From an initial Brinell hardness of below 200, deformation will raise the hardness to a maximum of about 550 Bhn., with an associated increase in yield and ultimate strength. Representative conventional tensile properties appear in Table 1, but the merit of manganese steel is better shown by the true stress at fracture, which is around 200,000 psi. for the standard grade. This value is attained because of the work hardening during tensile deformation, which absorbs much energy in the process.

Work hardening is usually induced by impact, such as from hammer blows. Light blows, even if of high velocity, will cause shallow deformation and hardening, although it may be locally intense. Heavy impact produces deeper hardening, usually with lower maximum values. The course of flow under impact and the associated rise in hardness are shown in Fig. 3. Heat *A* has 1.17% C, 12.8% Mn and 0.46% Si and was heated to 1850°F. and water quenched. Heat *B*, an air-hardening steel, has 0.74% C, 0.88% Mn, 0.30% Si, 0.75% Ni, 1.40% Cr and 0.38% Mo and was heated to 1650°F., air cooled, then reheated to 1200°F., and cooled in air.

The low yield strength range is significant, and will militate against selection of this alloy where practically no deformation is permissible, unless the usefulness of the parts in question can be restored by grinding. However, if deformation is immaterial, the low yield values may be considered temporary; that is, deformation will produce a higher yield strength through work hardening.

Tensile strength and ductility are affected somewhat by composition, as outlined above, by heat treatment and considerably by grain size, the finer grain specimens exhibiting as much as 30% greater strength and elongation. It should be noted that the values sometimes quoted for cast bars may reflect the effect of internal defects such as shrinkage cavities. The data herein refer to sound specimens. Aside from the minor influence of directional properties, the chief difference between cast and wrought manganese steel stems from the grain size effect.

The hardness of about 200 Bhn. after toughening has little significance for esti-

mating machinability or wear resistance. It will increase so rapidly from deformation that austenitic manganese steel must be evaluated on a distinctive basis.

Notch bar impact test values are very high (see Table 1). Charpy test specimens are sometimes bent and dragged through the machine rather than fractured. Like tensile properties, impact resistance is influenced by grain size and heat treatment. The alloy remains tough at subzero temperatures.

Resistance to crack propagation is high. This is associated with very sluggish progressive failures, permitting periodic observation of fatigue cracks, for example, and removal from service before complete failure occurs. This is a distinct advantage for railroad track work.

The low yield strength of austenitic manganese steels is sometimes a disadvantage. Plastic deformation from impact, as in railway frogs and crossings, raises it to more flow resistant levels, but the associated change in dimensions is undesirable. In track work low spots develop at critically pounded locations, resulting in a bumpy roadway and eventu-

Table 1—Properties of Hadfield's Austenitic Manganese Steel

(a) Chemical Composition

Type	Form	Composition, % C	Mn	Si	Ni
Std.	Cast 1 in. diam.	1.0 –1.4	10 –14	0.2–1.0	.....
Std.	Rolled 1 in. diam.	1.1 –1.4	11 –14	0.2–0.6	.....
Ni-Mn	Cast 1 in. diam.	0.59–0.91	12.4–14.3	0.48–0.90	3.4 –3.6
Ni-Mn	Cast 1 in. diam.	1.10–1.17	12.5–12.7	...	3.1 –3.6
Ni-Mn	Rolled 1 in. diam.	1.1 –1.4	10 –14	0.2–0.6	3.25–3.75

(b) Mechanical Properties

Type	Yield Strength, Psi.	Tensile Strength, Psi.	Elongation, %	Reduction of Area, %	Hardness, BHN	Vee-Notch Impact, ft.-lb. Izod	Charpy
Std.[a]	50,000–57,000	100,000–145,000	30–65	30–40	185–210	100	90–220
Std.[a]	50,000–60,000	131,000–142,000	40–60	35–50	170–200	...	90–150
Ni-Mn[a]	42,000–50,000	93,000–132,000	40–65	40–89	140–180	...	95–106
Ni-Nn[a]	....	113,000–140,000	44–70	35–45	150–170	...	105
Ni-Mn	50,000–63,000	130,000–155,000	48–72	40–60	165–195	...	90–150

[a] Toughened by water quenching.

(c) Physical Properties (All Types)

Work Hardening Capacity: From 170–200 Bhn. to 450–550 Bhn.
Specific Gravity: 7.9.
Density: 0.286 lb./cu. in. = 493 lb./cu. ft.
Melting Point: 2450°F.
Thermal Conductivity: 2.31 vs. copper at 100.
Electrical Resistivity: 70 microhms/cm. cube or about 7 times that of pure iron.
Electrical Conductivity: 0.0143 Megmhos per cm. cube.
Specific Heat (thermal capacity): 0.145 g. cal./gm./°C.
Thermal Conductivity (0.8% C, 3% Ni): 0.031 cal./cm.²/cm./sec./°C. = 90 Btu./sq. ft./in./hr./°F.
Magnetic Permeability: 1.003–1.03 (H = 24).
Magnetic Permeability (without surface preparation): 1.30 ±.
Wet Quartz Sand Abrasion Factor: 0.75–0.85 (vs. SAE 1020 as 1.00).
Thermal Expansion Coefficients, In. per In. per °F.:

	Average
100–300°F.	0.0000102
100–500°F.	0.0000113
100–700°F.	0.0000119

ally requiring rebuilding with weld deposits. Flow resistance and yield strength are intimately related, and a number of methods for increasing them have therefore been developed. Alloy additions and preservice hardening may be employed, the latter being more successful.

Wear Resistance

While 12% Mn steel is unquestionably the best metal for resisting certain types of wear, it is not universally applicable. The determining factor in its selection for abrasive service should be toughness, not abrasion resistance. If impact or shock are absent, as in a pipe carrying sand-laden water, a martensitic cast iron is a much better choice. If light or moderate impact is involved the specification of a hardened steel may be justified, but requires careful judgment in sacrificing toughness for abrasion resistance. If heavy impact is expected or a large safety factor is required, Hadfield's steel is the logical alloy, the large annual tonnage going chiefly into such applications.

It is sometimes believed that manganese steel has poor wear resistance if it has not been work hardened. This is not a valid generalization. It has probably developed because where much impact and attendant work hardening are present 12% Mn steel is so clearly superior to other metals that its performance is attributed to the surface hardening. Even without cold work it will frequently outwear chilled cast iron or pearlitic white cast iron and sometimes is only moderately less wear resistant than steels hardened by heat treatment.

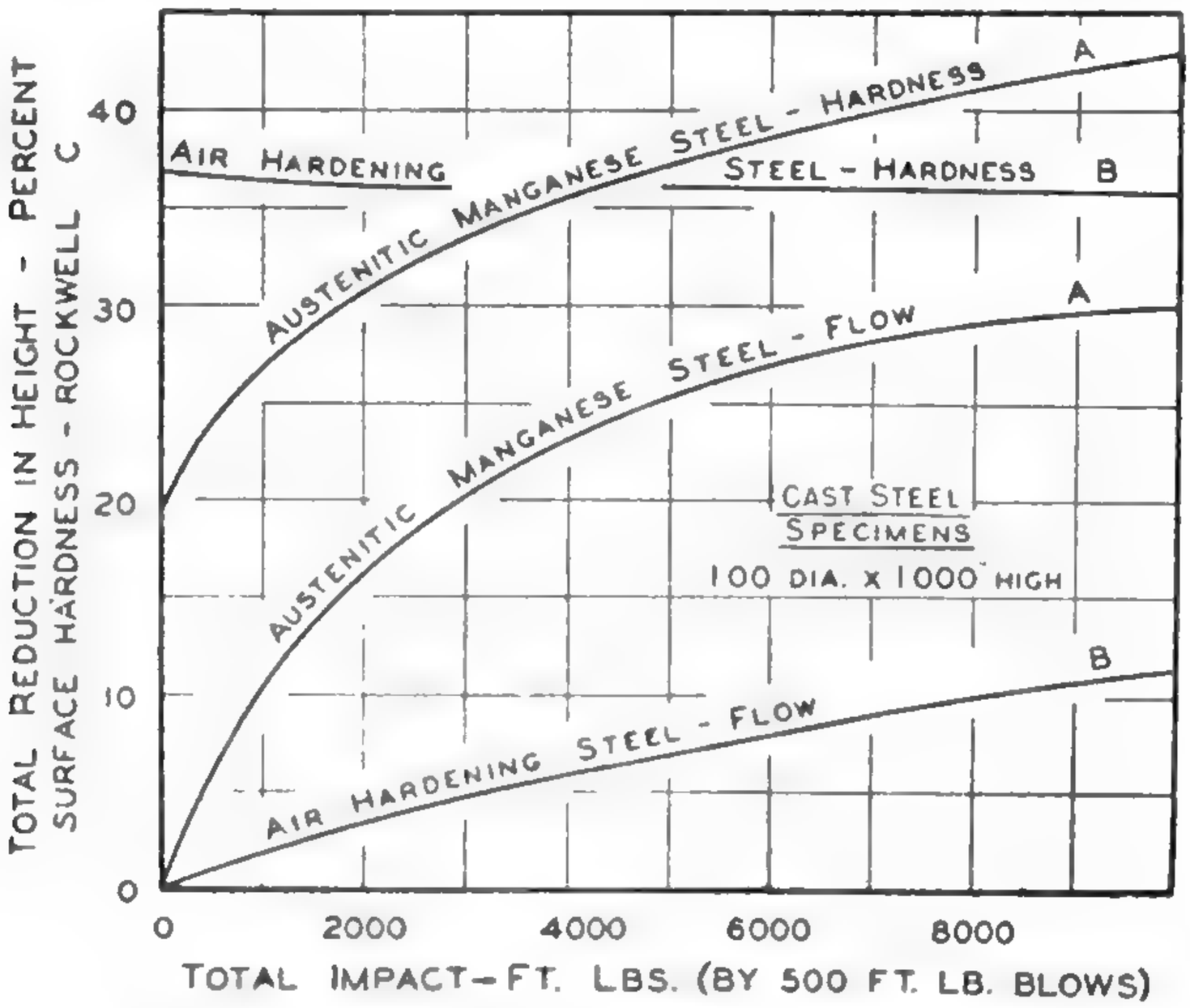


Fig. 3.—Plastic Flow and Work-Hardening Characteristics of Austenitic Manganese Steel Under Repeated Impact

Metallography

With its behavior of toughening after a water quench and embrittling after a tempering heat treatment, manganese steel appears as a paradox in contrast with conventional steels. However, an understanding of its sluggish transformation tendencies and their dependence on temperature indicates that the difference is more apparent than real. Above the *Acm* line (Fig. 1) it becomes completely austenitic. The austenite is not homogeneous in cast material as composition gradients result from the dendritic pattern of solidification.

Quenching, as with other steels, tends to suppress austenite transformation, with the difference that the critical cooling velocity is quite low below the austenite and carbide field. (Grain boundary carbide precipitation between *Acm* and A_1 is the primary cause of impaired properties associated with slow cooling.) Isothermal transformation between 600°F.

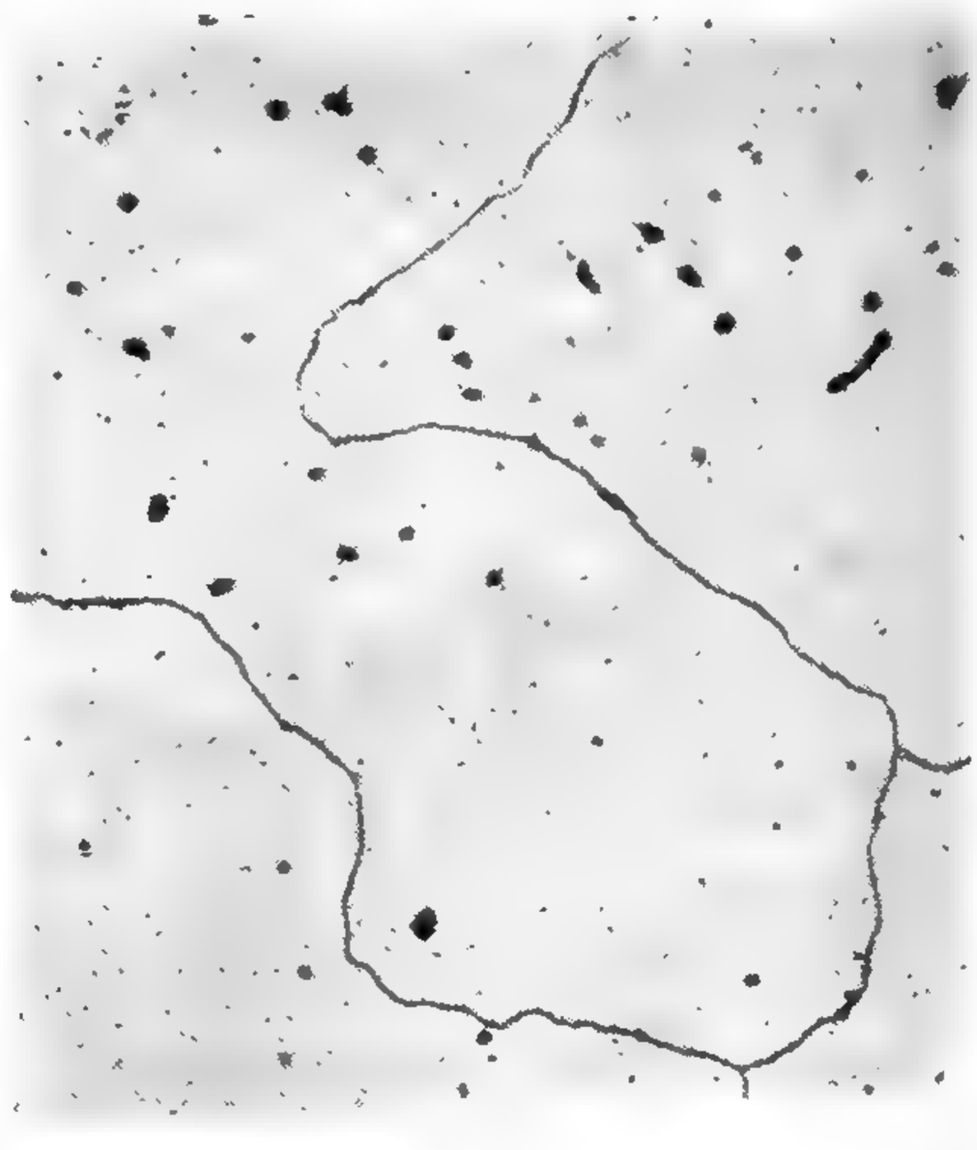
and A_1 will develop acicular or pearlitic structures, which appear slowly and require very long times for complete replacement of the austenite. As with mixed structures in other steels, the mechanical properties of partially transformed austenite are poor. They are particularly low when carbides or other brittle constituents form as large flat plates parallel to crystallographic planes. They are also low when pearlite, which seems to nucleate most rapidly at grain boundaries, develops in sufficient quantity to form an envelope around each grain. These structures account for the low ductility and reduced strength of the alloy after reheating.

100 ×

Fig. 4.—Manganese Steel As Cast

Some hardening is associated with reheating transformations. Hardening from pounding, which also involves transformation or carbide precipitation, is much more intense, however, and causes no sudden embrittlement, there being a gradual exchange of toughness for hardness.

Typical photomicrographs of austenitic manganese steels are shown in Figs. 4 to 8. The structure in Fig. 4 is as-cast and is as brittle as cast iron. The structure shown in Fig. 5 is composed entirely of austenite except for a few harmless inclusions and was produced by a toughening heat treatment. Figure 6 shows toughened manganese steel after deformation, the fine lines showing transformation or work hardening. Figure 7 shows the structure of a previously toughened steel that has been partially transformed and embrittled by heating for 6 min. at 1100°F.; Fig 8 shows the embrittlement produced by heating for 48 hr. at 800°F. In this last case the tensile strength dropped from about 139,500 to 95,000 psi. and the elongation in 2 in. from 47.5% to zero. Figure 9 shows the structure at the junction of a weld and casting. The weld deposit is of nickel-manganese steel and the casting of standard manganese steel. The parallel slip lines in both the weld and base metal are the result of deformation from peening the weld. The



100 ×

Fig. 5.—Austenitic Manganese Steel After Proper Heat Treatment

heavy grain boundaries are planes of weakness which have resulted from carbide precipitation induced by the heat of welding; the weld metal, because of its low carbon content, is relatively free from such precipitation.

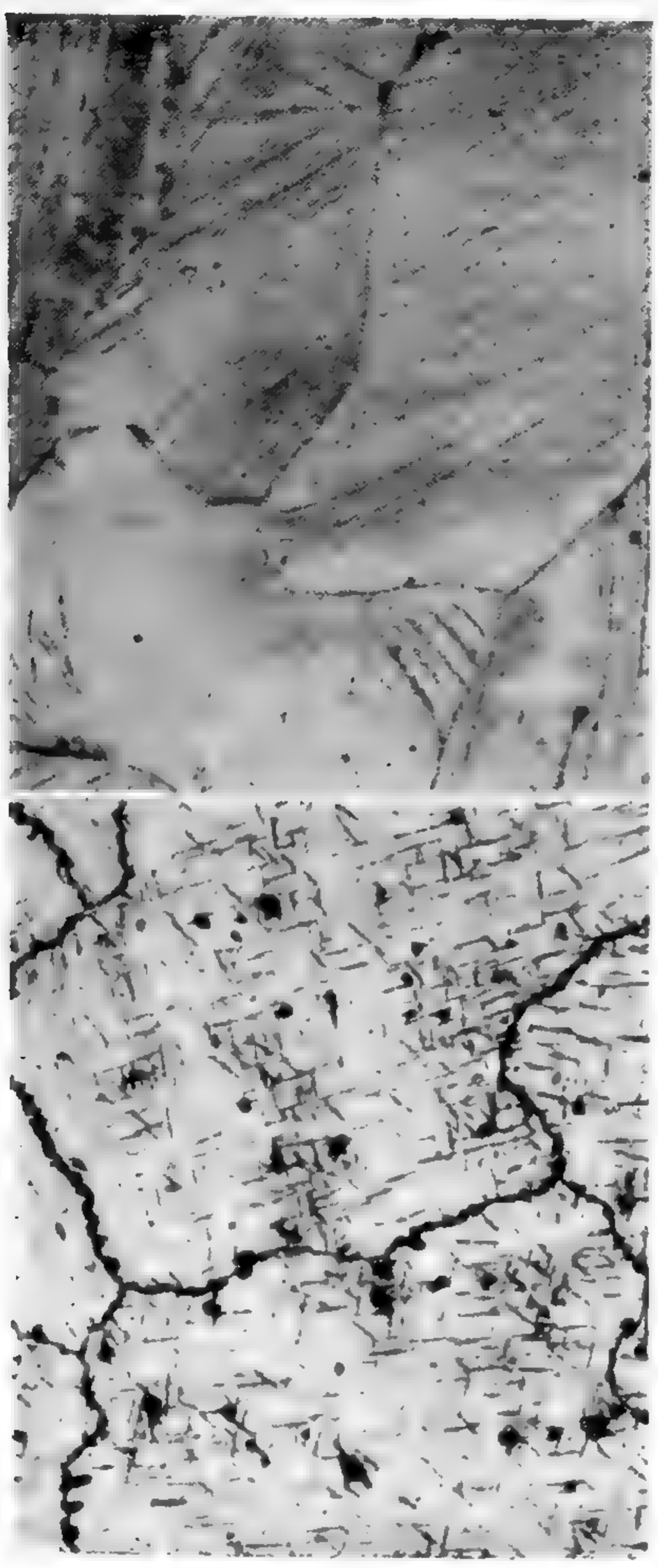
Nickel-Manganese Steels

Nickel additions to the standard grade of manganese steel produce no apparent change in yield strength but with the low-carbon nickel-manganese steels used for welding there is a distinct trend toward higher tensile elongation and a lower yield strength. Quenching rate is perhaps less critical, but quenching is still desira-

ble to obtain the maximum toughness. Such nickel additions stabilize the lower carbon types and, therefore, permit some control of the martensitic skin which may form during heat treatment.

Fig. 6.—Work Hardened Manganese Steel

100 ×



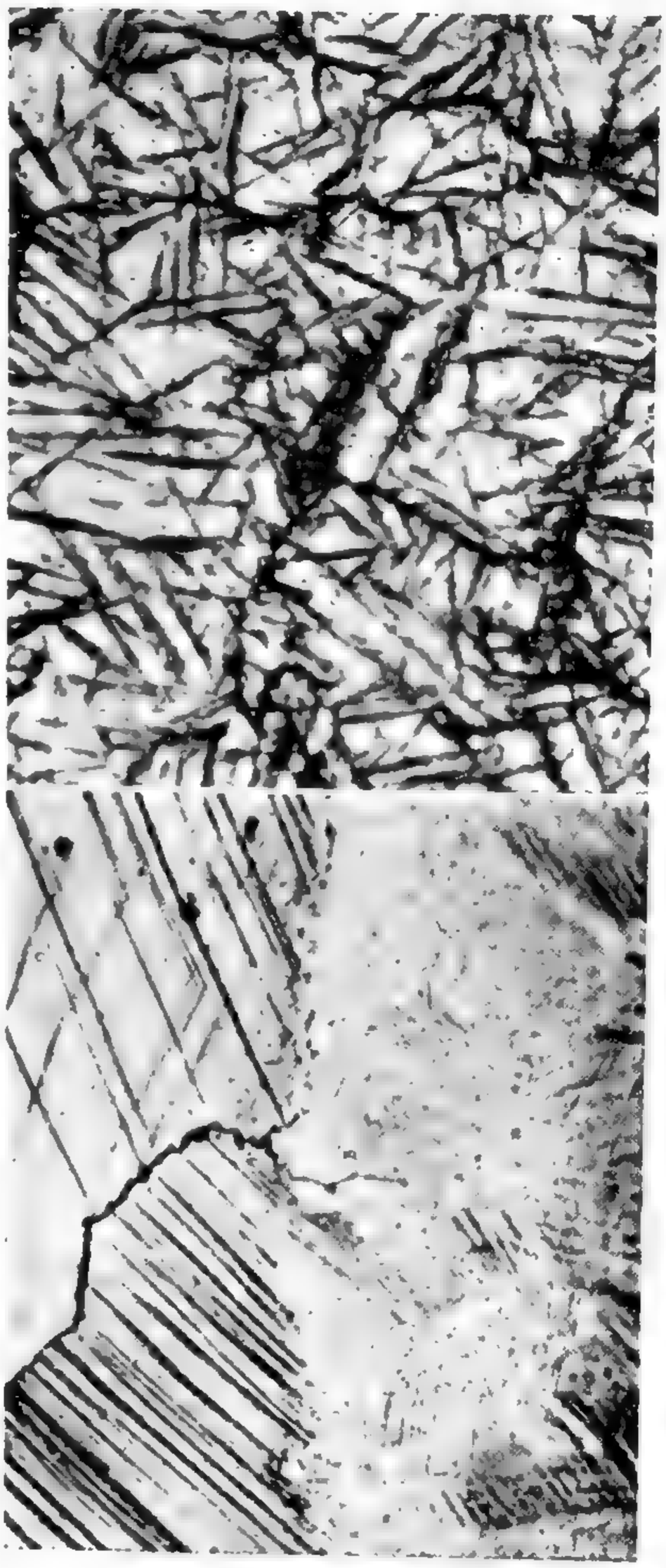
100 ×

Fig. 7.—Embrittlement Produced by Heating for 6 Min. at 1100° F.

A lower carbon content is much more effective in conferring toughness without quenching, and as added nickel seems to prevent the lower intrinsic toughness of the straight 12% Mn steels with low carbon, a group of steels with 0.60 to 0.90% C and about 3% Ni has become popular for welding rod, for wrought products and occasionally for castings. Representative properties appear in Table 2. This alloy exhibits greater resistance to embrittlement from reheating up to 800° F. than the standard grade.

Fig. 8.—Embrittlement Produced by Heating for 48 Hr. at 800° F.

250 ×



50 ×

Fig. 9.—Juncture of Weld Metal and Casting

HOW TO WELD

Only arc welding is recommended for welding austenitic manganese steel. The rapid loss of tensile strength and ductility which result from reheating toughened manganese steel, makes oxy-acetylene welding inadvisable because of the comparatively longer periods involved. Thermit welding with its characteristically slow cooling rate is generally not practiced unless subsequent heat treatment is practicable. Data regarding carbon arc and resistance welding are lacking, probably, in the case of resistance welding, because most welding of manganese steel is carried out in the field, where resistance welding operations are generally not feasible.

Arc welding electrodes of the following types are commercially available:

1. Bare Electrodes (3% Ni–14% Mn).
2. Covered Electrodes (3% Ni–14% Mn).
3. Covered Austenitic Stainless Steels (see Chapter 38).
4. Electrodes of low-carbon steel with high manganese coverings.
5. Composite electrodes with high manganese filler, with or without nickel, in a low-carbon steel tube.

Bare electrodes are commonly used where a high buildup is required or where slag removal is not practicable.

The best electrodes are those that contain the essential elements in a homogeneous core wire, either bare or with a covering that makes essential contributions to welding behavior, but not to deposit composition. Erratic performance may sometimes occur with use of composite electrodes since the brief interval during which the weld is molten is not conducive to proper mixing and alloying of the essential ingredients.

Ordinary steels should not be employed as electrodes, as the product of fusion will be a diluted manganese steel with poor mechanical properties.

Chromium-nickel stainless steels may be used to advantage in some cases as discussed later, but their expense is not ordinarily justified, and the welds will not be similar to the base metal in several properties.

In the previous section the properties of low-carbon nickel-manganese steel were

Table 2—Mechanical Test Properties of an Austenitic Nickel-Manganese Steel (Cast 1-In. Diam. Bars)

Chemical Analysis

C, %	Mn, %	Si, %	Ni, %
0.84	12.45	0.48	3.46

Tensile Properties After Toughening by Water Quenching from Above 1800°F.

Grain Size	Yield Strength, Psi.	Ultimate Strength, Psi.	Elongation in 2-In., %	Reduction of Area, %	Hardness, Bhn.
Coarse	44,500	106,250	49.5	41.2	174
Fine	45,700	121,750	60.0	41.5	174

Tensile Properties After Reheating the Toughened Steel

Reheating Temp., °F.	Reheating Time, Hr.	Grain Size	Ultimate Strength, Psi.	Elongation in 2-In., %	Reduction of Area, %	Hardness, Bhn.
500	48	Coarse	106,250	49.0	39.4	177
600	48	Coarse	106,500	50.0	42.7	174
700	48	Coarse	105,750	53.0	37.8	165
800	48	Coarse	105,250	47.5	41.5	174
500	48	Fine	123,750	62.5	40.3	174
600	48	Fine	125,000	63.5	39.7	174
700	48	Fine	125,500	61.0	40.0	172
800	48	Fine	127,000	65.0	42.1	179

Notched Bar Impact Toughness

Machine-Ground Vee-Notch Charpy Specimens

Energy Absorbed in Ft.-Lb.

At room temperature	94–106
At 100°F. below zero	74– 84

outlined. This is the recommended electrode material, although other elements, such as molybdenum, may be substituted for nickel with satisfactory results.

If manganese steel is deposited on carbon or low-alloy steel, the transition zone will ordinarily be too low in manganese and will develop a martensitic structure which, because of brittleness, can permit spalling of the weld deposit. If carbon steel must be joined to manganese steel to form a structural member, a layer of austenitic stainless steel should be used to separate the carbon steel and manganese steel as the dilution products thereby formed are not associated with the inferior properties mentioned above. Likewise, the use of a wear-resistant manganese steel overlay on carbon or low-alloy steel is not recommended, an air-hardening steel or alloy cast iron usually being more satisfactory.

The direct application of a surfacing material to manganese steel is both practicable and economical and is indicated where localized abrasion resistance and the inherent toughness of manganese steel are required. Such composite structures should follow the principle of having the base metal as the tougher of the two.

Welding Procedure

Arc welding procedure should be based upon:

(*a*) Welding only on sound, clean, un-work-hardened base metal that has been properly heat treated.
(*b*) Minimum heating of the base metal.
(*c*) Minimum mixing of deposited and base metal.
(*d*) Minimum thermal stresses in the weld deposit.

It should be remembered that castings, the most common form in which manganese steel is used, may contain gas cavities, spongy areas of shrinkage porosity, or entrapped sand. Any of these may be responsible for a fracture that will require repair by welding. If so, it should be removed before proceeding, as a satisfactory weld rarely results if the defect is directly covered over with weld metal.

During reheating, work-hardened steel embrittles more rapidly than the non-worked metal; for this reason, hardened metal should be removed by oxygen cutting and/or grinding. In the field a center punch mark produces a convenient test, grinding being continued until a deep indentation is readily produced.

The use of an ordinary hand magnet to distinguish between carbon steel and manganese steel provides a quick and reliable tool for field use. The hand magnet can also be used to determine whether manganese steel has been properly heat treated. If a weak magnetic attraction still persists after removing the surface layer by grinding, the piece has been either improperly heat treated or has been reheated in such a manner as to produce embrittlement. In this case it is better, if at all possible, to reheat treat the manganese steel part before attempting to weld.

Only limited base metal heating can be tolerated if the heat embrittled zone is to be kept at a minimum. Factors within the control of the welder to reduce base metal heating are short welding periods, short arc length, lowest possible current and the use of the smallest diameter electrode consistent with the thickness of the section being welded.

Minimum mixing of base metal with molten weld metal reduces the tendency to add more carbon from the base metal to the weld deposit than is desirable for toughness. Excessive mixing is, of course, also indicative of too much heat, with its embrittling tendencies.

Thermal stresses develop as the weld deposit contracts during cooling. With expansion coefficients about 30% greater than those of mild steels, and with a low thermal conductivity that tends to localize heating very sharply, the austenitic manganese steels characteristically develop high local stresses. Manganese steel has high ductility when strained in one direction, where the stretching of metal in this direction is compensated by the reduction in area in another direction. However, the two- and three-dimensional stresses that occur in weld deposits can and frequently do cause failure with no apparent ductility. The stress system is chiefly responsible, and the easiest remedy lies in the modification of the stresses. These are tensile stresses in a weld bead, but they may be changed to compressive stresses by peening the deposit. Such peening flows the outer surface and the deformation relieves the tension that would otherwise cause cracks.

Both bare and covered electrodes are

used for welding within the approximate current ranges shown in Table 3:

Table 3—Suitable Current Values for Nickel-Manganese Steel Welding Electrodes

Bare Electrodes		Covered Electrodes	
Electrode Diam., In.	D.C. Reverse Polarity, Amp.	D.C. Reverse Polarity, Amp.	A.C., Amp.
1/8	80–100	75–105	80–110
5/32	90–125	85–130	90–135
3/16	110–150	100–155	110–160
1/4	135–160	110–170	135–175

Oxygen cutting of manganese steel parts is practiced extensively in the field for joint preparation of manganese steel parts, and also in general fabrication work. Although oxy-acetylene welding usually produces a wide zone of embrittlement through a prolonged heating period, oxygen cutting, because of the rapid application of heat, usually does not produce enough embrittlement to cause difficulty.

Recommended Welding Techniques

To illustrate the general procedures and cautions outlined in the previous section, detailed welding techniques for a few of the more commonly encountered field applications are outlined below:

Depositing a Manganese Steel Weld Bead.—Before welding, the surface should be ground or wire brushed to remove all dirt and scale. Using the proper welding current (from Table 3) the electrode is gripped at a point about halfway along its length and the arc is struck. The electrode should be deposited using a weaving technique with the electrode held at about a 45-deg. angle in the direction of welding. The width of weave should be two to three times the diameter of the electrode and the arc length approximately equal to the electrode diameter (see Fig. 10).

A crescent weave permits the deposited metal to remain molten for a longer time than with the conventional weave used for welding mild steel. Gas which might otherwise be entrapped can readily escape from the molten pool and the resulting heavy bead serves to reduce the danger of cracks which sometimes occur because of improper welding technique.

Welding is stopped by drawing the electrode back into the weld deposit and breaking the arc after about one half of an electrode has been deposited. Care must be taken to fill the crater to the full weld size before breaking the arc to avoid crater cracks. Immediately after welding is stopped, the crater should be peened; then the entire weld is peened proceeding in the direction of welding from the start to the end of the weld.

A pneumatic hammer is preferred for peening, but if this is not available, a machinist's ball peen hammer may be used. Another alternative is to use an ordinary chisel with the cutting edge rounded off to the desired radius. This is sometimes advantageous in that the root pass of a deep single-vee weld can be reached, whereas a ball peen hammer is usually ineffective in such locations.

After peening, the arc is restruck ahead of the crater and then drawn back to where the crater begins as shown in Fig. 10, so that a smooth continuous bead is obtained without cracks at the restarting point.

Welding should not be started again if the base metal temperature at a distance of 1/2 in. from the weld is above 400 to 500°F.

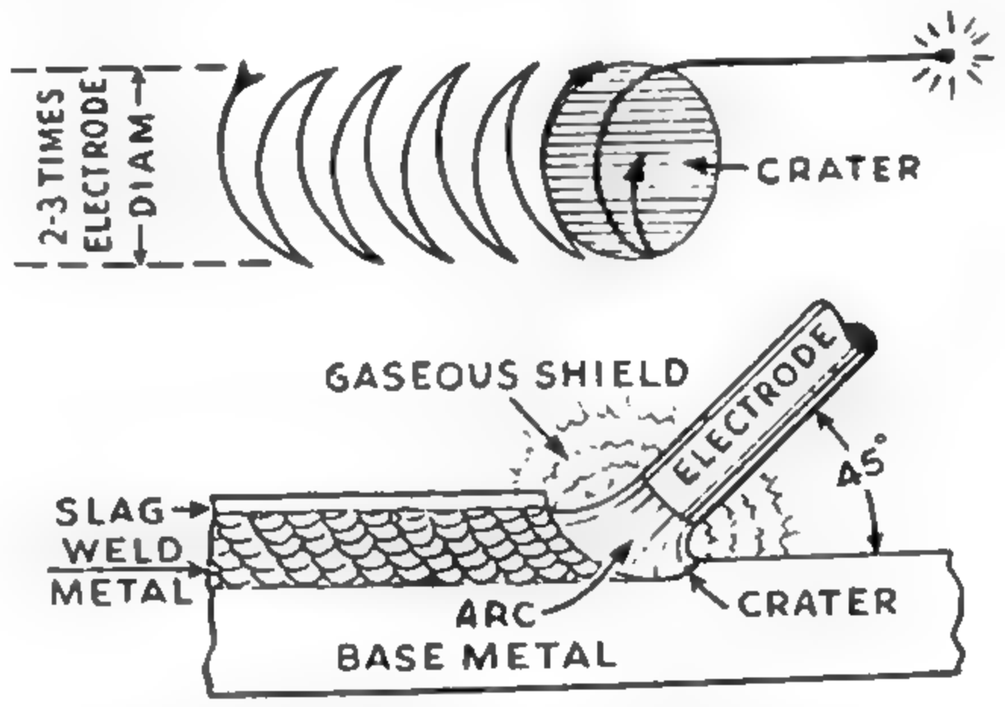


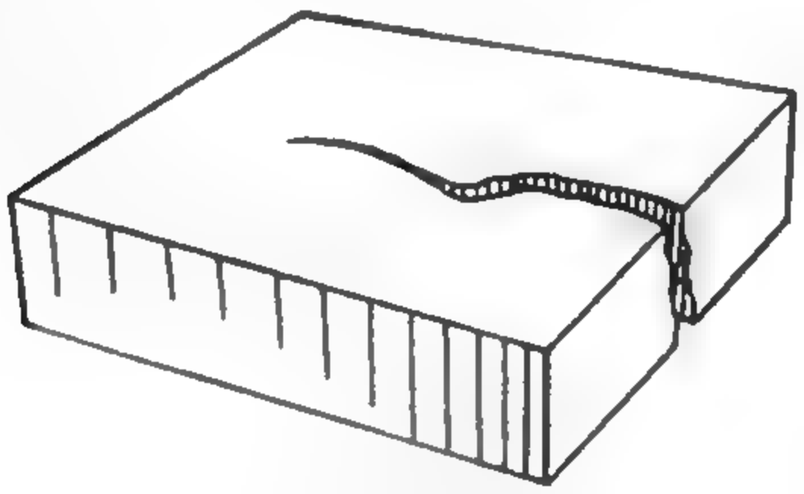
Fig. 10.—Technique for Filling Crater in Depositing Manganese Steel Weld Bead

Repairing Cracks.—Cracks may sometimes occur in manganese steel parts subjected to long and abusive service. In many cases the service life of these parts can be prolonged substantially by repair welding of the cracks using the following procedure.

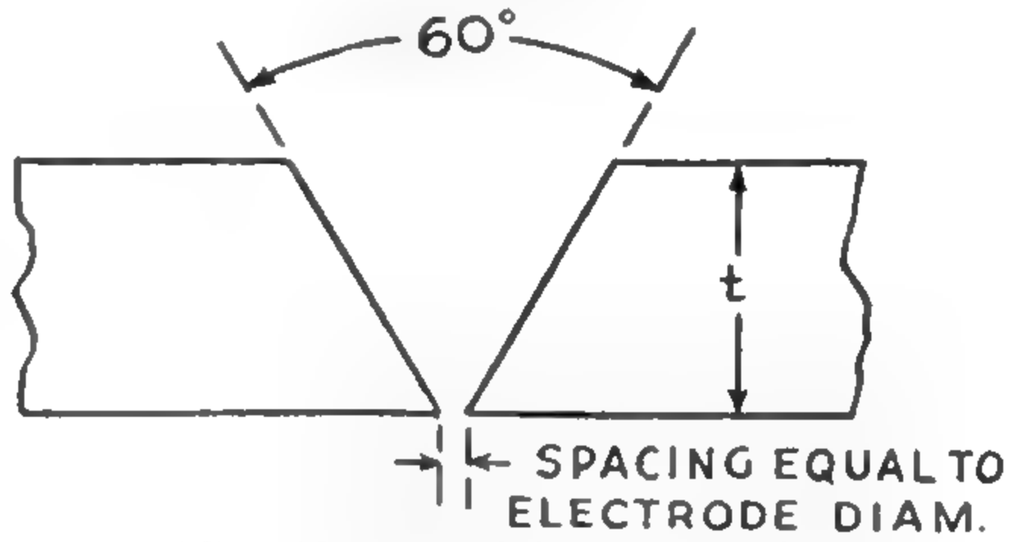
A typical crack is shown in Fig. 11 (*a*). A hole is burned at the end of the crack with an oxygen-cutting torch as shown in Fig. 11 (*b*). This prevents further propagation of the crack under stresses imposed by subsequent welding. A single-U groove, as shown in Fig. 11(*c*), is then gouged out to a depth equal to two-thirds the thickness of the section,

care being taken to avoid overheating of the base metal. The width of the groove at the top should be about equal to its depth. (An alternative joint preparation is shown in Fig 11 (*d*).) The surfaces are then ground or wire-brushed to remove any oxides, dirt, scale, etc.

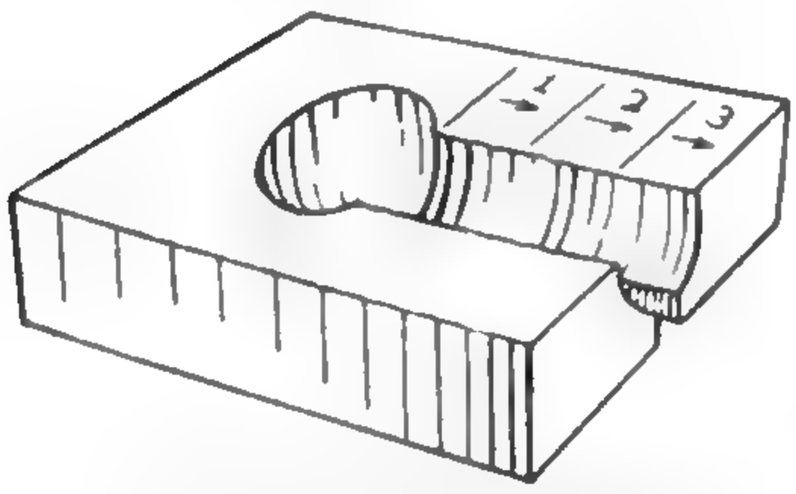
ing at the beginning of the weld and progressing in the direction of welding. The first 2 to 3-in. section (point *1*) is built up completely by successive passes, each pass being peened before depositing the next successive pass. Additional 3-in. sections are then built up as shown by



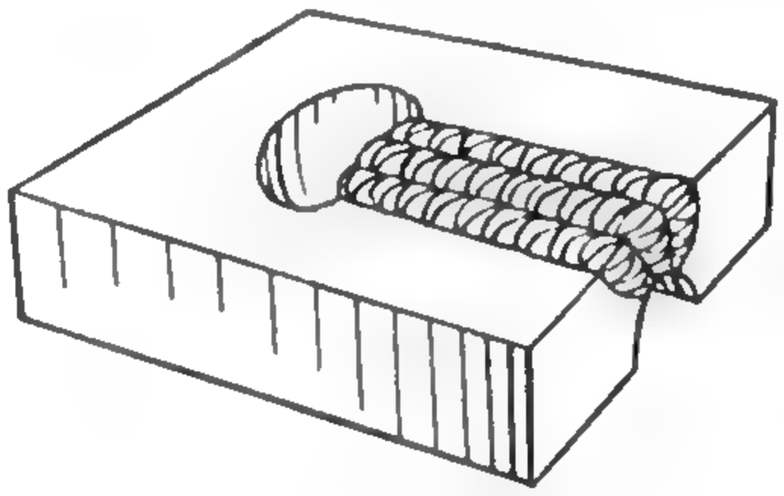
(*a*) Cracked member.



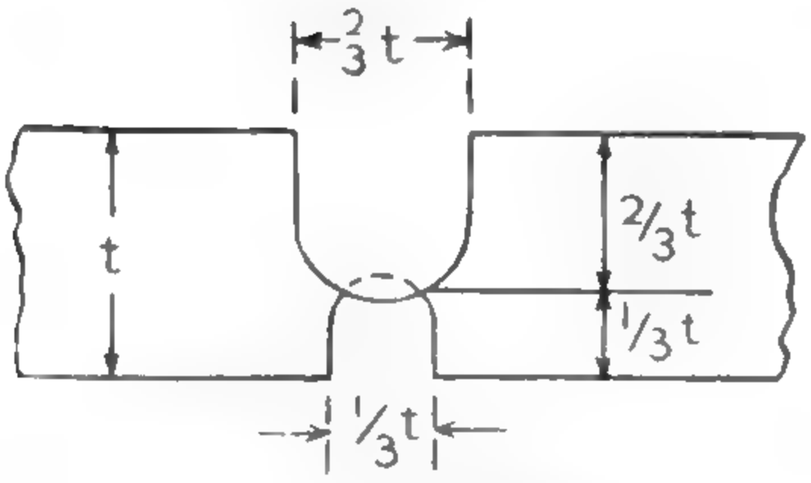
(*d*) Alternate joint preparation.



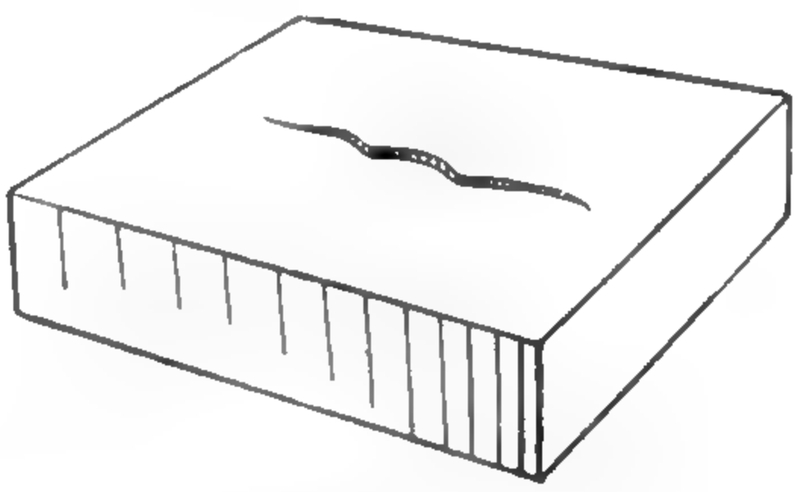
(*b*) Initial joint preparation.



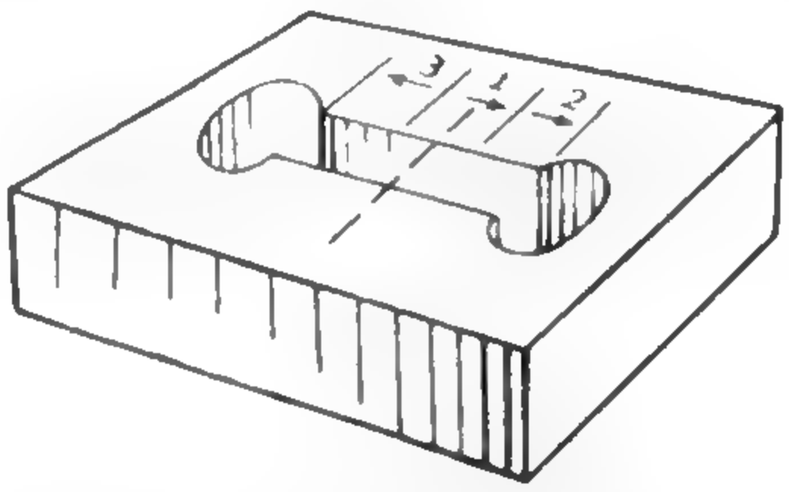
(*e*) Welding sequence.



(*c*) Joint preparation.



(*f*) Internal crack.



(*g*) Initial joint preparation.

Fig. 11.—Repair of Cracks in Manganese Steel Part

Welding is started at point *1* (Fig. 11 (*b*)) and a heavy root bead, about 2 to 3 in. long deposited before the arc is broken. The crater is peened first and then the entire weld bead is peened start-

points *2* and *3* in Fig. 11 (*b*) in the same manner as just described.

A single-U groove is then gouged out on the other side to a depth equal to one-third the thickness of the section as shown

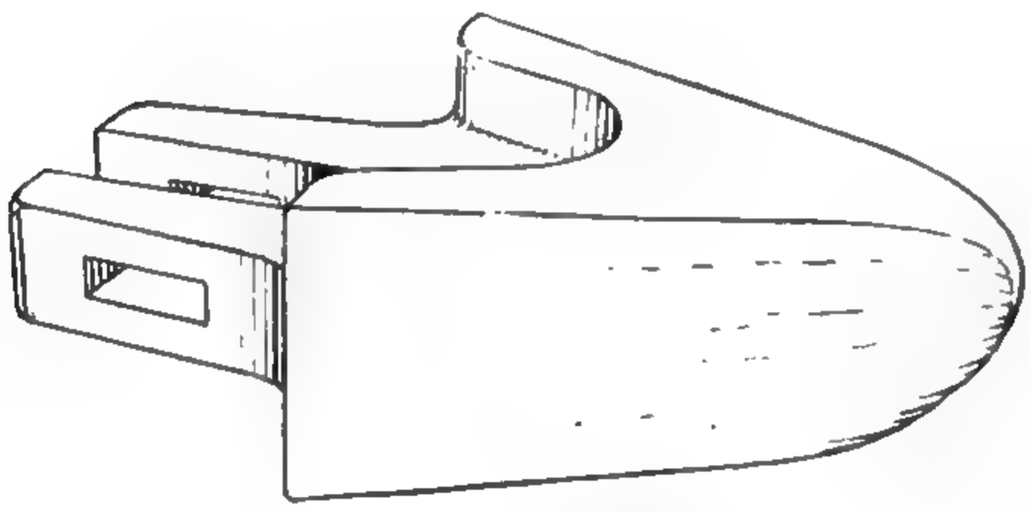
in Fig 11(*c*) (bottom). This groove is then welded up by a series of short beads following the procedure previously described for depositing a manganese steel weld bead. It is not necessary to build up each 3-in. section completely as on the first side before proceeding with adjacent 3-in. sections. After the crack is completely welded, the hole made before welding is rewelded (see Fig. 11 (*e*)).

The procedure for repairing internal cracks, as illustrated in Fig. 11 (*f*) follows, for the most part, the procedure described above, the difference being that two holes are cut to prevent crack propagation and a slightly different welding sequence is used as shown in Fig. 11 (*g*).

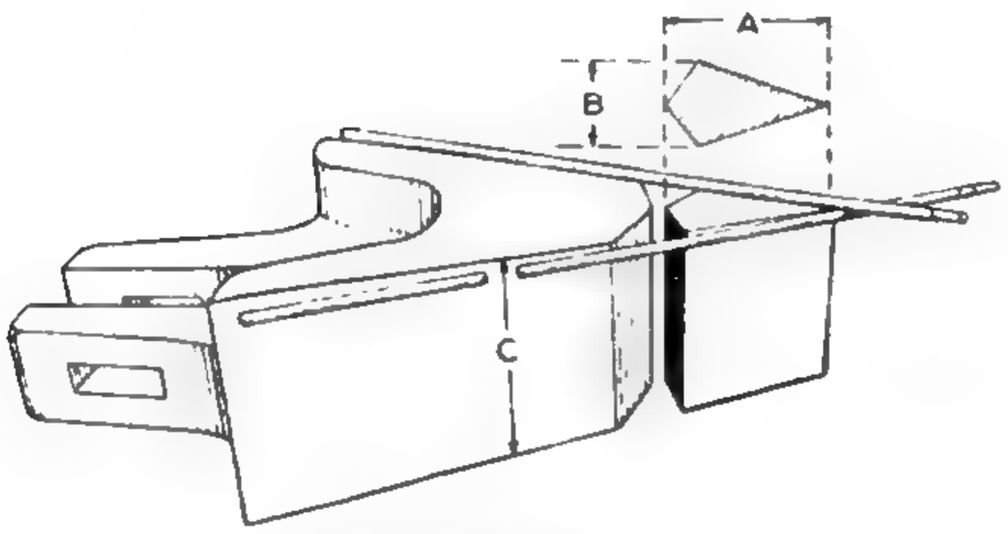
Repointing of these teeth, through the use of commercially available *repointer bars* has come to be a reliable and quick means of obtaining increased service life. These bars can be obtained in a wide variety of shapes and sizes in the form of cast or rolled bars, and can be oxygen cut to the required width in the field. They are attached by welding as follows:

A worn tooth is shown in Fig. 12 (*a*). A beveled edge is oxygen cut on the worn tooth as shown in Fig. 12(*b*). This serves to remove the work-hardened zone, on which welding should not generally be attempted.

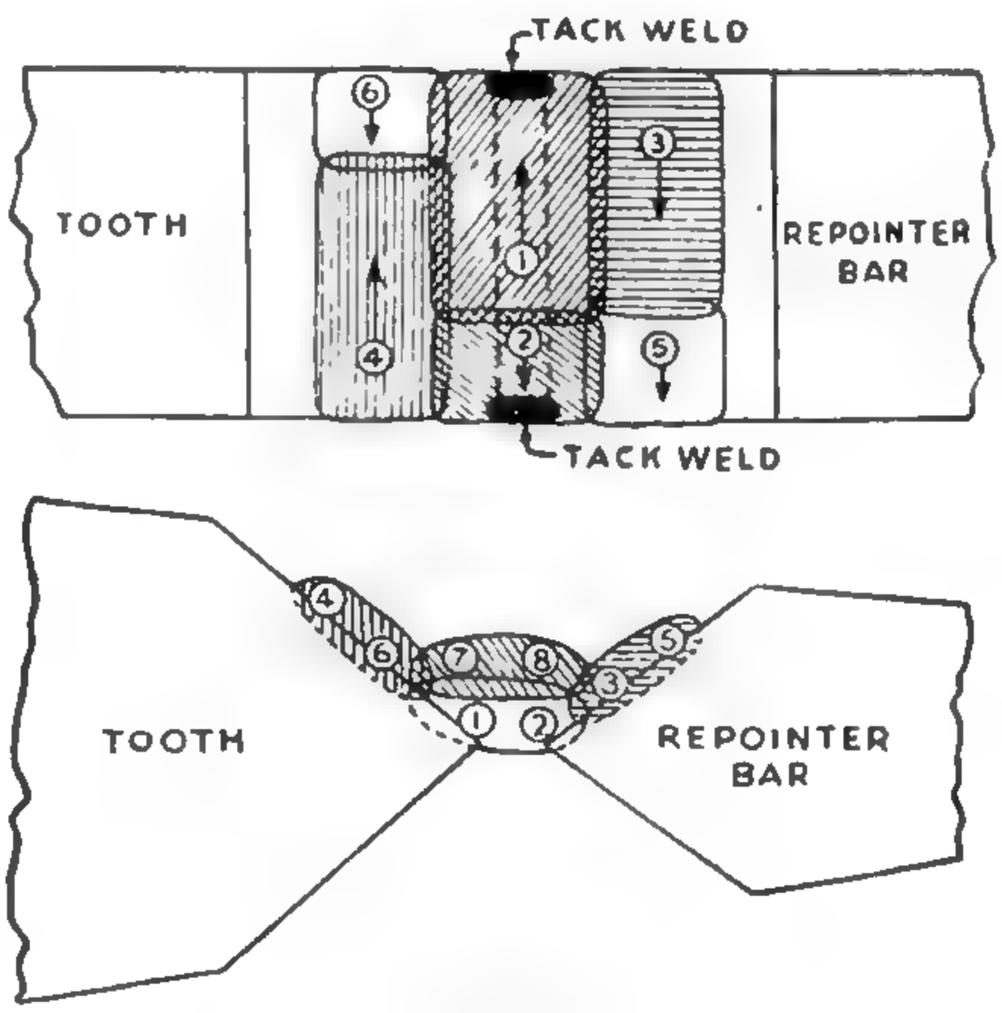
The size and shape of the repointer bar are determined by measuring dimensions



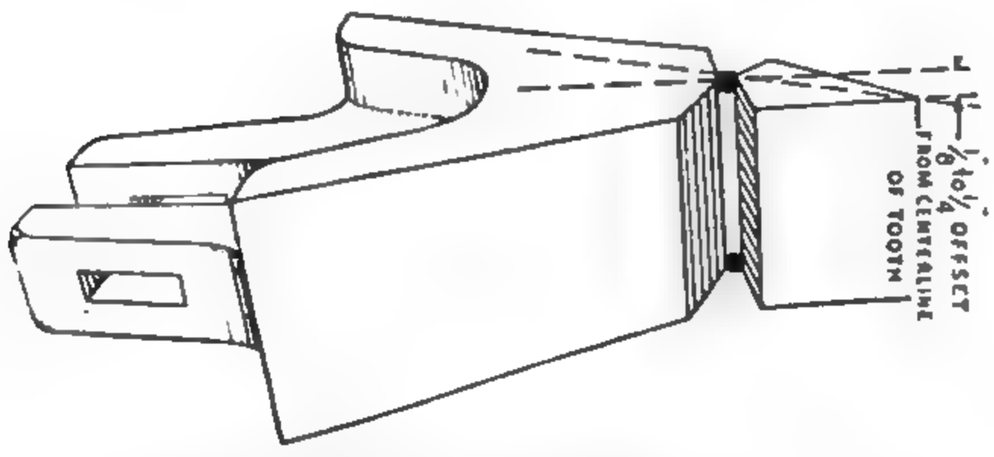
(*a*) Worn tooth.



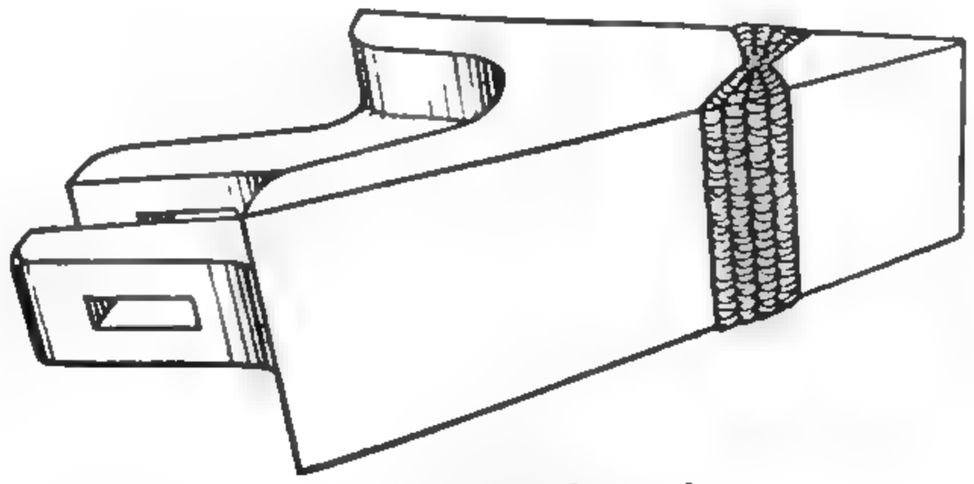
(*b*) Preparation of tooth and selection of repointer bar.



(*d*) Welding sequence.



(*c*) Repointer bar tack welded to tooth.



(*e*) Repointed tooth.

Fig. 12.—Repair of Worn Dipper Tooth

Repointing Worn Dipper Teeth.—Teeth on power shovel dippers, drag line buckets, clamshell buckets, trencher buckets, scarifiers and similar equipment sometimes wear rapidly where impact and severe abrasive conditions exist together. Repointing of these teeth, through the use of commercially available *repointer bars* has come to be a reliable and quick means of obtaining increased service life. These bars can be obtained in a wide variety of shapes and sizes in the form of cast or rolled bars, and can be oxygen cut to the required width in the field. They are attached by welding as follows:

A worn tooth is shown in Fig. 12 (*a*). A beveled edge is oxygen cut on the worn tooth as shown in Fig. 12(*b*). This serves to remove the work-hardened zone, on which welding should not generally be attempted.

The size and shape of the repointer bar are determined by measuring dimensions *A* and *B* shown in Fig. 12 (*b*). This can be done by laying electrodes or straight edges along both faces of the worn tooth. The point of intersection of the two electrodes or straight edges will immediately indicate the shape of the repointer bar

required and will provide a reference point for measurements to determine the size bar required. With these factors as a guide, selection may be made from several available styles depending principally on whether a blunt or sharp-pointed tooth is needed.

Having selected a repointer bar it is oxygen cut to the width of the tooth as shown at point *C* in Fig. 12 (*b*). It is then tack welded to the worn tooth on both sides, the bar being offset from the tooth as shown in Fig. 12 (*c*), leaving a root opening about equal to the diameter of electrode being used.

Welding is started as shown in Fig 12(*d*), following the procedure previously described. When the center-line of the repointer bar is drawn into line with the center-line of the tooth by the welding, the tooth is reversed and welding started from the opposite side following the welding sequence shown in Fig. 12 (*d*) until each side is reinforced by the same amount of weld metal. Welding is continued alternately on each face until the joint is completed after which the tooth is turned on its side and several beads are deposited. The same operation is performed on the remaining side, taking care in each instance to see that the ends of all weld beads are tied together. After welding is completed, the two faces subject to the greatest amount of wear may be surfaced to prolong the life of the tooth. The repointed tooth is shown in Fig. 12 (*e*).

The teeth and lip of a dipper for use in an iron ore mine, as surfaced for better abrasion resistance, are shown in Fig. 13.

COMMON APPLICATIONS

The important applications of austenitic manganese steel are in the industries of construction, mining, quarrying, oil-well drilling, manufacturing of steel, railroading, manufacturing of cement and clay products, dredging and lumbering. This steel serves chiefly as parts in equipment for handling materials, rock crushers, grinding mills, dredge buckets, power-shovel buckets and teeth, pumps for handling gravel and rocks and in a multitude of associated applications. An important use is in railroad track work, such as frogs, switches and crossings, where the multiple impacts at intersections are especially severe. Austenitic manganese steel resists metal-to-metal wear; therefore, it may be used in sprockets, pinions, gears, wheels, conveyor chain and various wearing plates, shoes or other contact members. Nonmagnetic parts, required for lifting-magnets, for induction furnaces and special electrical equipment, represent an expanding field of usefulness.

Fig. 13.—Dipper Teeth and Lip Surfaced with Abrasion Resistant Alloy

BIBLIOGRAPHY

1. *Wearing Tests on 12% Manganese Steel,* J. H. Hall, Proceedings of the American Society for Testing Materials, 1928.

2. *Studies of Hadfield's Manganese Steel with the High Power Microscope,* J. H. Hall, Transactions of the American Institute of Mining Engineers, 1929.

3. *A study of the Constitution of High Manganese Steels,* V. N. Krivobok, Transactions of the American Society of Steel Treaters, 1929.

4. *ASTM-ASME Symposium on Effect of Temperature on Metals,* American Society for Testing Materials, 1931.

5. *Equilibrium Diagram of Iron-Manganese-Carbon Alloys of Commercial Purity,* E. C. Bain, E. S. Davenport and W. S. N. Waring, Transactions of the American Institute of Mining Engineers, 1932.

6. *Relative Wear of Metals Due to Abrasion,* C. R. Weiss, Iron Age, 1932.

7. *Welding Special Ferrous Alloy Castings—A Review of the Literature to November 1, 1936* W. Spraragen and G. E. Claussen, The Welding Journal Res. Suppl., June 1937.

8. *Welding Manganese Steels*—A Review of *the Literature to July 1, 1937,* W. Spraragen and G. E. Claussen, The Welding Journal Res. Suppl., August 1938.

9. *Some Things We Don't Know About the Creep of Metals,* H. W. Gillett, Transactions of the American Institute of Mining Engineers, 1939.

10. *Steel and Its Heat Treatment,* D. K. Bullens, John Wiley & Sons, 1939.

11. *Metallographic Identification of Ferro-Magnetic Phases,* H. S. Avery, V. O. Homerberg, and E. Cook, Metals & Alloys, November 1939.

12. *Quantitative Measurement of Strain Hardness in Austenitic Manganese Steel,* D. Niconoff, Transactions of the American Society for Metals, 1941.

13. *Hadfield Mn Steel—Another Approach to Its Qualities and Use,* V. R. Farlow and L. H. McCreery, Metals & Alloys, November 1941.

14. *Mechanical Properties of Iron-Manganese Alloys,* F. M. Walters, Jr., I. R. Kramer and B. M. Loring, Transactions of the American Institute of Mining Engineers, 1942.

15. *Avoiding Cracked Castings,* The Amsco Bulletin, reprinted in Metals and Alloys, May 1942.

16. *High Manganese Austenitic Steels,* R. Franks, W. O. Binder and C. M. Brown, Iron Age, October 1, 1942.

17. *The Mass Production of a Manganese Steel Casting,* J. W. Gardom, Transactions of the American Foundrymen's Association, 1943.

18. *Some Aspects of Strain Hardenability of Austenitic Mn Steel,* D. Niconoff, Transactions of the American Society for Metals, 1943.

19. *High Mn Stainless Steels,* D. J. Mack, Metals & Alloys, September and November 1943.

20. *Influence of Hydrogen on Mechanical Properties of Some Low-Carbon Mn-Fe Alloys and on Hadfield Mn Steel,* H. H. Uhlig, Transactions of the American Institute of Mining Engineers, 1944.

21. *A Metallographic Study of the Decomposition of Austenite in Mn Steel,* J. V. Russell, and F. T. McGuire, Transactions of the American Society for Metals, 1944.

22. *An Emergency Heat Resistant Alloy,* O. E. Harder and J. T. Gow, Transactions of the American Society for Metals, 1944.

23. *The Effect of Cold Rolling on the Structure of Hadfield Mn Steel,* Norman P. Goss, Transactions of the American Society for Metals, 1945.

24. *Austenitic Manganese Steel,* H. S. Avery and M. J. Day, Metals Handbook, American Society for Metals, 1948.

25. Amsco Bulletins, American Manganese Steel Division of American Brake Shoe Co.

(a) *Mn Steel for the Construction Industry,* Bulletin No. 1143-CI.

(b) *Mn Steel for General Industry,* Bulletin No. 543-G.

(c) *Mn Steel for Mining & Quarrying Equipment,* Bulletin No. 743-M.

(d) *Mn Steel for the Clay Products Industry,* Bulletin No. 1243-CP.

(e) *The Amsco Bulletin,* 1944.

(f) *Mn Steel for the Railroad Industry,* Bulletin No. 943-R.

(g) *Mn Steel in the Steel Industry,* Bulletin No. 1142-SM.

(h) *Mn Steel for Cement Mill Equipment,* Bulletin No. 1043-CM.

(i) *Mn Steel for All Dredging Purposes,* Bulletin No. 844-D.

(j) *Mn Steel for the Lumber Industry,* Bulletin No. 144-L.

(k) *Mn Steel for Apron Feeders,* Bulletin No. 643-AF.

(l) *Mn Steel for Oil Field Service,* Bulletin No. 244-P.

(m) *Mn Steel for Crusher, Grinding Mill and Pulverizer Parts,* Bulletin No. 642-C.

(n) *Mn Steel for Wheels & Rollers—Car, Conveyor, Crane, Gear Sheave, Sprocket and Miscellaneous,* Bulletin No. 842-WS.

(o) *Non-Magnetic Applications for Mn Steel,* Bulletin No. 1144-NM.

CHAPTER 32

ALUMINUM AND ALUMINUM ALLOYS*

GENERAL PROPERTIES

MOST OF THE commercial welding processes have been adapted to joining aluminum and aluminum alloys. Correct application of these processes involves an understanding of the technique required to produce good results. Economical design of welded parts requires some knowledge of the physical and metallurgical properties of the materials. This chapter proposes to outline the essential characteristics of equipment and technique required to make welds and to incorporate some established design and constructional details.

Mechanical and Physical Properties

Considering first the materials which are of importance from the welding standpoint, aluminum alloys can be divided into two categories—wrought and cast. The mechanical properties of the wrought materials are shown in Table 1, of aluminum sand castings in Table 2 and permanent mold castings in Table 3. The nominal composition of these materials is shown in Table 4. Other physical properties which are useful when considering welding procedure or design are shown in Tables 5 and 6. These tables do not show all of the aluminum alloys as many special-purpose materials have been developed. It is suggested that the supplier be consulted for information on the weldability of alloys other than those shown. By similarity in composition, mechanical and physical properties, it is frequently possible to find listed in the tables materials having welding characteristics comparable to those of alloys not listed.

Commercial Forms and Tempers.— Aluminum alloys are produced in many forms. Wrought alloys in the form of sheet and plate, tubing, extruded shapes and forgings have similar welding characteristics regardless of the form. Aluminum alloys are also produced as castings in the form of sand, permanent mold or die castings. Both sand and permanent mold castings are welded in the foundry to effect minor repairs and in combination with most of the wrought forms. Substantially the same welding practices are used on both cast and wrought metal. Those special practices of advantage on cast parts will be described in more detail later. Die castings have not been widely used where welded construction is required. A limited use has been made of flash welding but other welding processes have not been developed for die cast parts. Special aluminum products, such as foil or wire, are welded using practices specially adapted to thin sections.

Metallurgical Effects of Welding

An understanding of the metallurgical effects of welding aluminum and aluminum alloys requires some basic knowledge of the properties and structures. There are two broad classifications of aluminum alloys, i.e., nonheat-treatable and heat-treatable. Strengths of pure aluminum and the nonheat-treatable alloys are developed by strain-hardening and by alloying elements which effect some increases in strengths either as dispersed phases or solid solutes in the aluminum. Manganese is the principal dispersoid type alloying element and alloy 3S the chief example. Magnesium is the principal soluble alloying element in the nonheat-treatable class of aluminum alloys, with 4S and 52S the chief examples. In the annealed or soft temper (-O) the composition of the alloy wholly

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* Prepared by a committee consisting of G. O. Hoglund, Aluminum Company of America, *Chairman*; A. G. Bissell, Bureau of Ships; J. J. Chyle, A. O. Smith Corp.; F. E. McAtee, Chicago Bridge and Iron Co.; G. Perkins, Reynolds Metals Co; D. W. Smith, Permanente Metals Corp.; F. J. Winsor, Standard Oil Co. of Indiana.

controls the strengths while in the strain-hardened or (-H) series of tempers the degree of strain-hardening is the controlling factor.

The alloying elements in heat-treatable aluminum alloys are dissolved in the aluminum at a high temperature by the process commonly known as *solution heat treatment* and maintained in solid solution by quenching from this temperature. The solution of specific elements or compounds in aluminum governs the strengths of these alloys in the as-quenched temper. Additional increases in strengths are effected by precipitation of a portion of the soluble elements in finely divided form. Precipitation may take place at room temperature following quenching or may be accelerated by a thermal treatment at a moderately elevated temperature (usually in the range 210 to 350°F.), producing the -T4 or -T6 tempers, respectively. Alloys susceptible to either of these precipitation treatments are designated as *age-hardenable*. Strengths may also be increased by strain-hardening after heat treatment which may or may not be followed by artificial aging. In the annealed or soft temper (-O) the composition of the alloy wholly controls the strengths as in the case with the nonheat-treatable alloys.

The heat-treatable alloys can be divided into classes containing the following principal alloying elements:

Element	Alloy Examples
a—Mg and Si	53S, 61S, 63S, R353 and R361
b—Cu and Mg, Cu, Mg and Si	24S, 14S and Hard-clad R301
c—Zn, Mg and Cu	75S
d—Si	43, 355 and 356

The heat of welding decreases the strengths of both nonheat-treatable and heat-treatable aluminum alloys except when in the annealed or the as-cast condition and may in some cases also lower their resistance to corrosion. The effects of strain-hardening in the nonheat-treatable class are partially or wholly destroyed by heat, depending upon the temperature attained coupled with the time maintained at temperatures of about 400°F. or more. The effects of solution heat treatment and precipitation treatments for the heat-treatable aluminum alloys are adversely affected by the heat of welding. The extent of the detrimental effect increases with temperature and time at temperatures over 400°F. The alloys containing substantial amounts of copper suffer not only from loss of strength but also from loss in resistance to corrosion when subjected to the heat of welding.

The factors determining the heat of welding are multiple; however, two of the controlling conditions in welding are (1) the melting point of the base material and (2) the melting point of the filler metal. The exact thermal cycle through which the materials progress or the rate of heating and cooling is determined mainly by (1) the welding process, (2) the thickness of the part and (3) the geometry of the joint.

In welded joints there are always two types of material to be considered; i.e., the weld metal or deposit which has a cast structure and the base metal which may be wrought or cast. The mechanical properties of cast aluminum in the weld zone are influenced by the composition and the rate of solidification. In general, for a given aluminum alloy, cast metal is neither as strong nor as ductile as wrought metal.

When filler metal is used, the weld deposit is an alloy formed from a mixture of the filler metal with the base metal. The extent of fusion and intermixing of the base metal and added weld metal, in multiple-pass welds, is a function of the filler metal, plus the welding procedure. A high rate of cooling is usually desirable for attainment of maximum strength.

Alloys do not solidify at a fixed temperature but over a range as shown in Tables 5 and 6. Solidification begins at the liquidus and is complete at the solidus with a resultant mixture of solid and liquid extending over what is called the mushy stage. It is preferable that filler metal have a low melting point and solidify over a temperature range. When the welding pool freezes, the filler metal solidifies last and the contraction stresses that are sometimes sufficient to cause cracking at the edge of the weld are taken up by the casting in the mushy state. The filler metal must have a high degree of fluidity, and have sufficient strength and ductility at elevated temperatures to withstand the stresses imposed by the thermal and solidification contractions. Since the fusion zone is apt to be weak in welds of aluminum alloys, the importance of the composition

and structure of these alloys must be recognized.

The selection of filler metal is based on welding characteristics, such as fluidity and cracking tendency and on corrosion or strength requirements. The alloy 2S (commercially pure aluminum) is employed as filler metal when maximum resistance to corrosion and high ductility are of prime importance in the weldment. The alloy 43S is generally employed for greater strength and avoidance of cracking. Other aluminum alloy filler metals are employed on occasion for specific applications when the strength or resistance to corrosion requirements of the weldment are such that special procedures or welding technique must be employed.

C. Solid solution	Region where heat from welding is high enough to dissolve soluble constituents which are partially retained in solid solution if cooling is sufficiently rapid.
D. Partially annealed and overaged	Region where heat from welding causes precipitation of soluble elements to the extent that partial annealing occurs and region where precipitation associated with an overaged condition occurs.
E. Unaffected	Region where heating does not affect the structure.

A cross-section through the weld and base metal is shown in Fig. 1 with microstructures of the various areas.

The widths of these areas and their distances from the weld will vary with the welding process and the thickness or

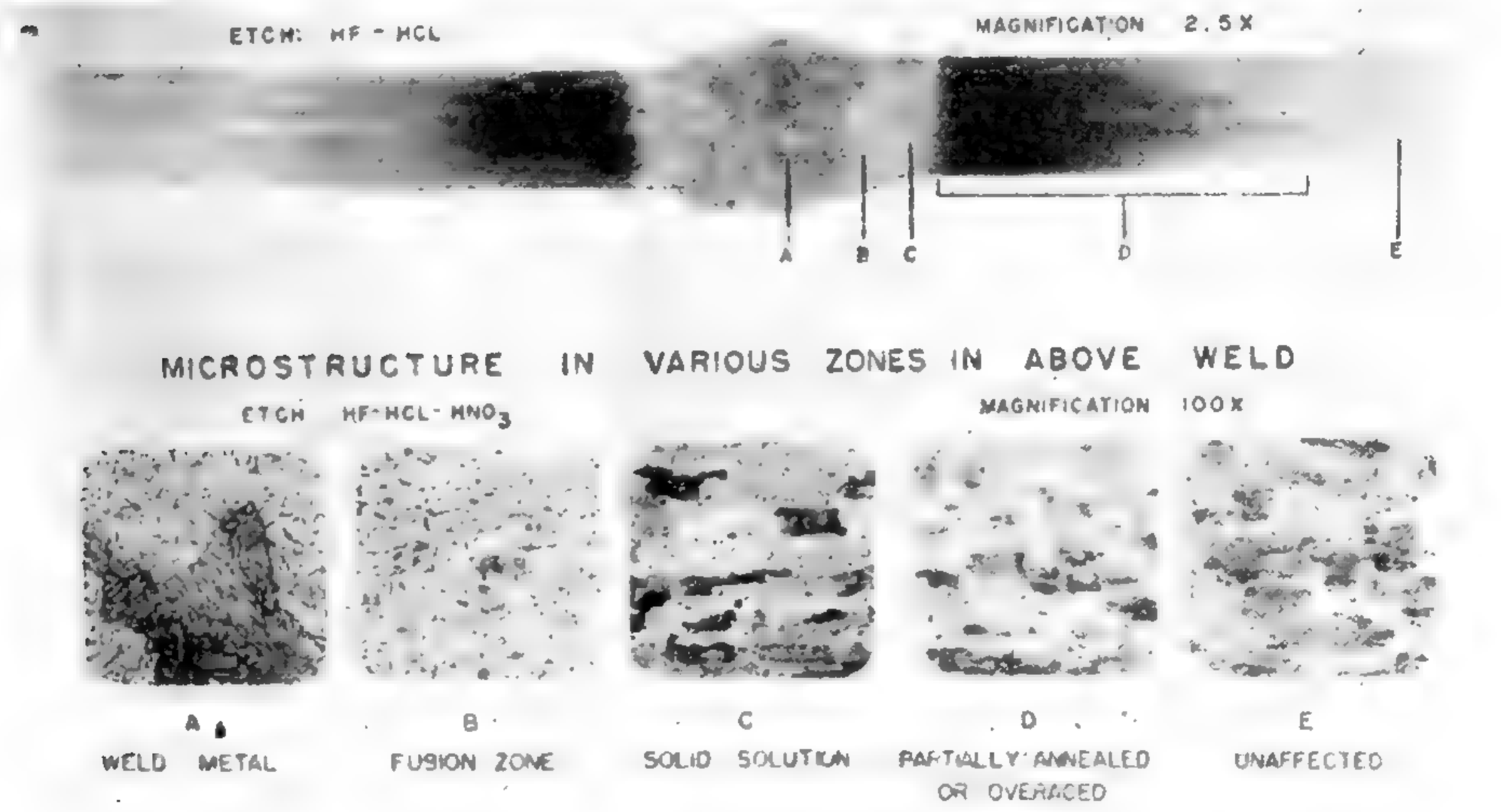


Fig. 1.—Cross-Section of Arc Weld in Heat-Treatable Aluminum Alloy (14S-T6). (3/8 Original Size)

The effect of welding upon the aluminum base metal varies with the distance from the weld and may be divided roughly into areas which reflect the temperatures attained by the metal. Obviously these areas or zones are not sharply defined as the heat distribution changes from point to point. For the heat-treatable alloys, five zones may exist as follows:

Zone	Description
A. Weld metal	Weld bead with as-cast structure where base metal is alloyed with weld metal.
B. Fusion zone	Region where partial melting of base metal occurs at grain boundaries.

geometry of the part. The strengths of the base metals may be fairly high in the solid solution area which is always quite narrow. The annealed area is broader—usually extending about four to six times the thickness of the material on each side of the joint—and the strength in these areas is considerably lower due to the precipitation of soluble constituents as coarse particles. The overaged zone is characterized by excess precipitation of finely divided particles. Strengths are somewhat lower than those of the unaffected zone at a greater distance from the weld.

The areas for the nonheat-treatable alloys are usually limited to three as follows:

Zone	Description
A. Weld metal	Weld bead with as-cast structure where base metal is alloyed with weld metal.
B. Annealed	Region where heat from welding causes recrystallization or annealing.
C. Unaffected	No change, original condition.

A cross-section through the weld and base metal is shown in Fig. 2 with microstructures of the various areas.

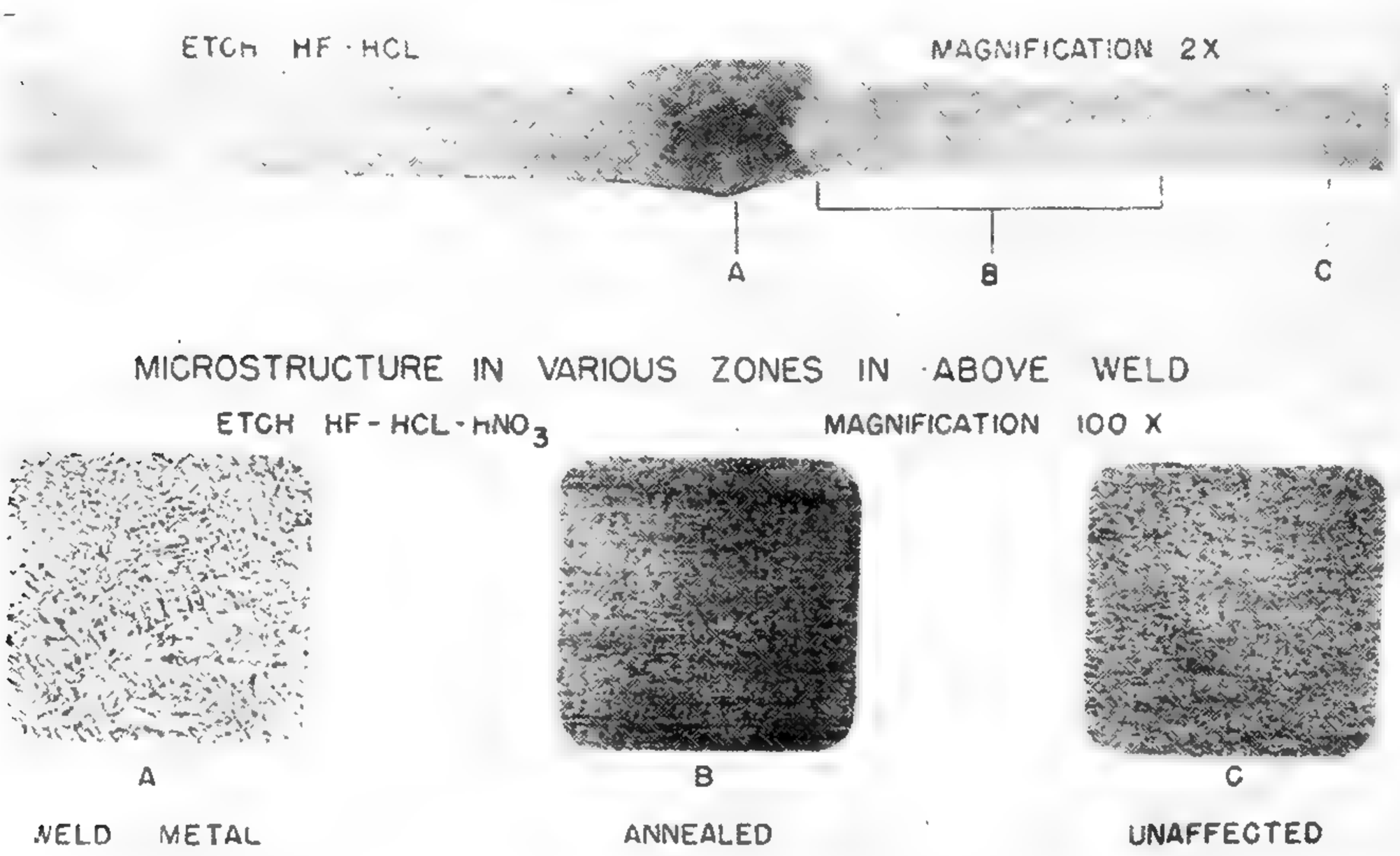


Fig. 2.—Cross Section of Arc Weld in Nonheat-Treatable Aluminum Alloy (3S).
(1/2 Original Size)

Gas welding usually affects a wider area than welding by the inert-gas metal-arc or shielded metal-arc welding processes.

Postheat treatment after welding is sometimes feasible for heat-treatable alloys and results in a substantial increase in joint strength. The design and geometry of the part determine the practicability of such an operation. Heat treating after welding dissolves soluble constituents in the weld metal and the coarse and fine precipitated particles in the base plate. A more homogeneous condition results throughout both the cast and wrought materials. Quenching retains this solid solution condition while subsequent precipitation, at room temperature or at a moderately elevated temperature, when artificial aging is employed, takes place fairly uniformly in the form of finely divided particles. Thus the maximum strength and resistance to corrosion of the base plate are realized, with some sacrifice in ductility. The strength of the joint is dependent upon that of the cast material in the weld zone.

The metallurgical effect when welding the heat-treatable cast alloys is similar to that described above for the wrought materials. Foundry welding to salvage cast parts by repairing defects is frequently required. In this case, welding should be completed prior to heat treatment. The welding of cast to wrought parts as in the joining of cast fittings to tubing or tankage is also done. Some impairment of heat treatment in the casting results from welding and this must be considered in arriving at the cross-sections to carry the loads. It is not usually feasible to heat treat after welding castings to wrought parts.

HOW TO WELD

General Use of Fluxes

When welding the aluminum alloys by gas, metal-arc, carbon-arc or atomic hydrogen welding and for all brazing processes, a flux is used to remove or break up the oxide coating. All aluminum materials are covered with an oxide coating

that varies in thickness, depending on the alloy and the conditions to which the parts have been exposed. Fluxes are used to break the oxide film so that it does not interfere with the deposition of filler metal or remain in the weld as an inclusion.

For gas welding, atomic hydrogen welding or brazing, these fluxes are usually applied in a mixture of about $^2/_3$ flux to $^1/_3$ water by weight. The mixture is dipped, painted or sprayed on the parts and the welding rod. In automatic carbon arc welding where a flux feeder is usually employed, it is more convenient to use the flux in the form of a dry powder.

Practically all aluminum welding fluxes contain chlorides and fluorides. Residual deposits on the joints after welding will, in the presence of moisture, attack the base metal. Thorough cleaning is necessary on parts that are to be painted as the paint will not adhere in the presence of flux. Several methods are used for this purpose, depending on the size and shape of the parts. If the part can be immersed immediately after welding and all surfaces are accessible, cleaning can be done with a fiber brush and boiling water. Large chemical tanks cannot be immersed conveniently and are cleaned by scrubbing the joints with a brush and a stream of fresh water and then rinsing.

Parts such as airplane gasoline tanks, beer barrels, and other enclosed vessels usually have the joints located so that mechanical loosening of the flux deposit is not feasible. In these cases an acid dip is used, the part being immersed in dip tanks so that the acid contacts both the inside and the outside surfaces. Immersion in cold 10% sulfuric acid for 30 min., or in 5% sulfuric acid held at 150°F. for 5 to 10 min., is frequently used for flux removal. Immersion in cold 10% nitric acid for about 10 to 20 min. is also used. In all cases, the acid dip must be followed by rinsing in hot or cold water. A corrosion inhibitor in the form of 5% sodium or potassium dichromate is sometimes added to the rinse water and has a beneficial effect, particularly on gasoline tanks. Certain commercial cleaning systems have also been found satisfactory for the removal of flux.

It is sometimes desirable to remove the welding flux and obtain a uniform etched finish in the same operation. This can be done by immersing the part for 10 to 15 min., depending on the amount of etching that is desired, in a wood tank containing a solution of 10% nitric acid* and 0.25% hydrofluoric acid.* The bath tank and the cold water tank should be constructed of wood (cypress preferred) caulked with an asphalt-base caulking compound, and painted inside and outside with 4 or 5 coats of short-oil phenolic resin varnish or acid-resistant material. After draining the acid completely from the part, it should be immersed in cold water. This is followed by a hot water rinse in which the time of immersion should not exceed 3 min. to avoid staining of the etched surface.

The efficiency of the cleaning operations can be checked with an acidified solution of 10% silver nitrate. This is done by applying a few drops of distilled water to the surface where the presence of welding flux is suspected. After a few moments, enough of the flux will go into solution in the water so that if a drop or two is collected and in turn dropped into the silver nitrate solution a white precipitate will be formed if flux is present on the part. If the solution remains colorless, it can be assumed that cleaning operations have been adequate.

Filler Metal

Welding Rods.—The proper choice of welding rods for gas welding is important, particularly when joining alloys with comparatively large amounts of alloying constituent. Commercially pure aluminum and metal of higher purity are generally welded with the same grade of filler metal as the base metal. Commercially pure aluminum is also used for welding the aluminum-manganese alloy. In welding other wrought aluminum alloys, a welding rod containing approximately 5% silicon is generally used. This rod has a lower melting point than pure aluminum and permits the dissipation of some of the stress set up by solidification shrinkage and thermal contraction which occurs in the weld zone as it cools. Cracks in the weld and in the transition zone on parts that are welded in jigs can be minimized by using this type rod.

In welding castings to wrought parts, the 5% silicon aluminum alloy rod is the most widely used filler material re-

* Commercial acids.

gardless of the casting alloy. In welding castings in the foundry to repair misruns or to build up sections locally, welding rod of the same composition as the casting is used.

Electrodes.—The standard electrode for shielded metal-arc welding aluminum is 5% silicon-aluminum alloy and is suitable for general purposes. In a few cases where special exposure conditions exist, as for certain chemical equipment, it is necessary to use a core wire of the same composition as the base metal. For applications of this type, special electrodes are prepared from high purity metal or from the special alloy used for base metal. Such electrodes must usually be specially ordered as there is not sufficient general usefulness for these compositions to permit stocking. (See Chapter 38 for more detailed information on aluminum filler metal.)

Shop Practices

The fabrication of welded aluminum tankage or structural parts is handled in the shop under the prevailing conditions that exist for fabricating other materials. Storing, handling or forming these materials does not require special practices from the welding standpoint. Contamination of the aluminum parts with heavy metals such as copper or iron from tools used on these materials is sometimes important from the standpoint of resistance to corrosion and should be avoided. The weldability, however, is not affected.

Finish

It is necessary to finish the weld bead on some parts for reasons of sanitation or appearance. On equipment for handling food or chemicals where a smooth, easily cleaned surface is desired, butt welds are dressed by hammering. This is done by chipping the edge of the weld bead flush with the surface of the base metal, and then hammering the balance of the bead over a back-up block with blows heavy enough to work the metal through the entire cross-section. This practice differs somewhat from conventional peening used on welds in other metals, in that more than the surface of the weld is worked by the hammering.

Fillet welds in tee and corner joints are finished by grinding. The tendency to load up the conventional grinding wheels with aluminum can be overcome by using felt base wheels. The grinding compound is applied by rolling the edge of the wheel in glue, followed by rolling in abrasive compound graded in fineness from 60 to 200, depending on the surface required on the finished part. Buffing and color buffing operations are performed on welds in the same manner as on the parent metal.

Distortion

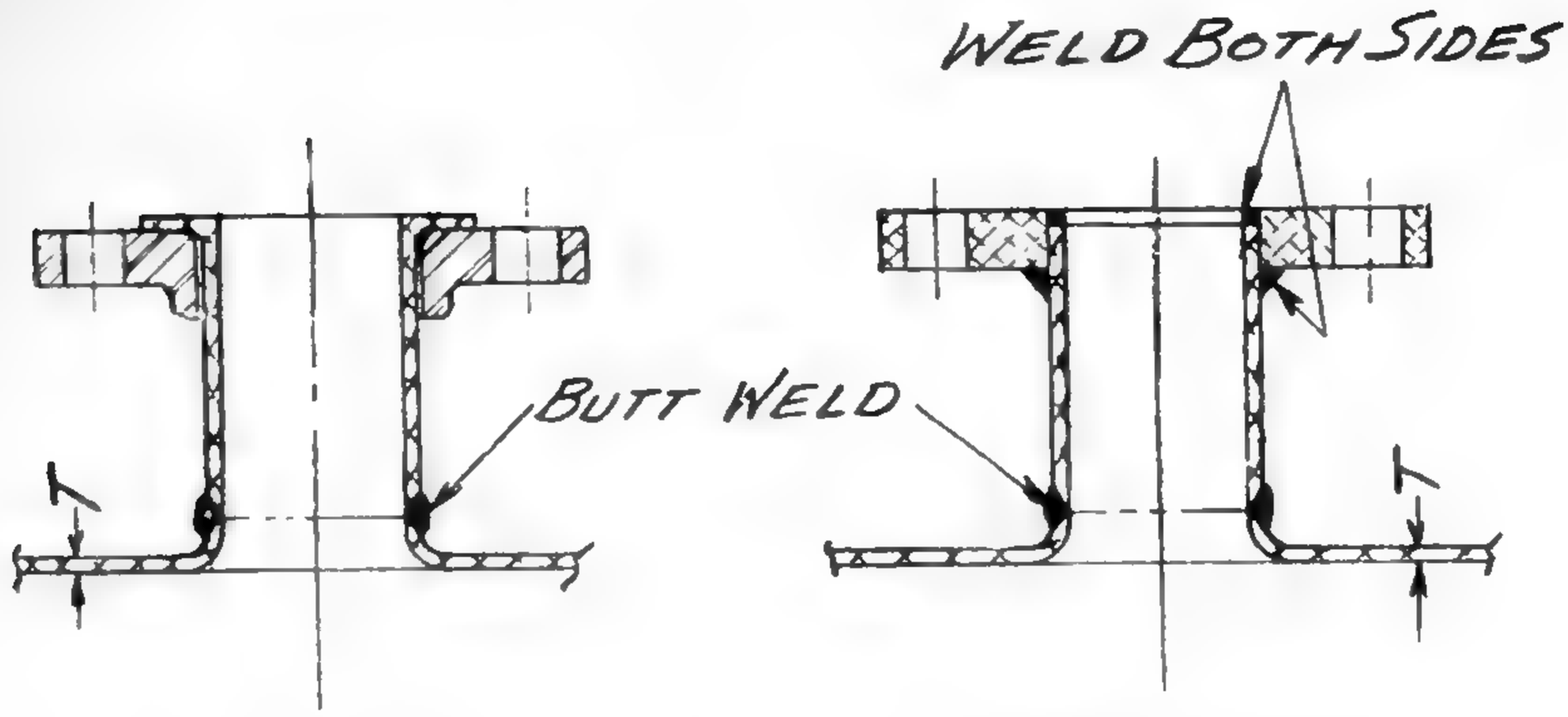
Because the aluminum alloys have a relatively high coefficient of thermal expansion compared to most weldable metals, it is important to minimize buckling and distortion from the welding heat by proper design and preparation of joints. On parts with flat sides, minimum distortion is obtained when the weld is located on an edge or a corner. Designs with crowned surfaces are better than flat surfaces from this standpoint. The location of welded seams or fittings in flat areas should be avoided. For parts subjected to pressure, the most economical design is the butt joint. This is true on cylindrical vessels even though minimum distortion is obtained if the heads are reversed and edge-welded in place.

The use of cold packs in the form of water-soaked rags or carbon backings to control distortion is only of assistance in isolated cases when gas welding the aluminum alloys. Because of the thermal conductivity of the metal, heat is removed from the weld zone by the above expedient so rapidly as to accelerate the solidification of the molten metal. This rapid cooling must be balanced by an increase in the flame size, with a consequent tendency to produce distortion of the parts.

In attaching manhole connections and fittings to tanks, it is desirable to flange the sidewalls and butt weld the fittings. In view of the ease of forming and the ductility of aluminum, this is generally not difficult. Typical practices for attaching fittings are shown in Figs. 3 and 4.

Gas Welding

The commonly used gas-welding processes for aluminum and aluminum alloys are oxy-hydrogen and oxy-acetylene welding. Equally good results from the standpoint of soundness, strength, speed and appearance are obtained with either process. Standard equipment in the way

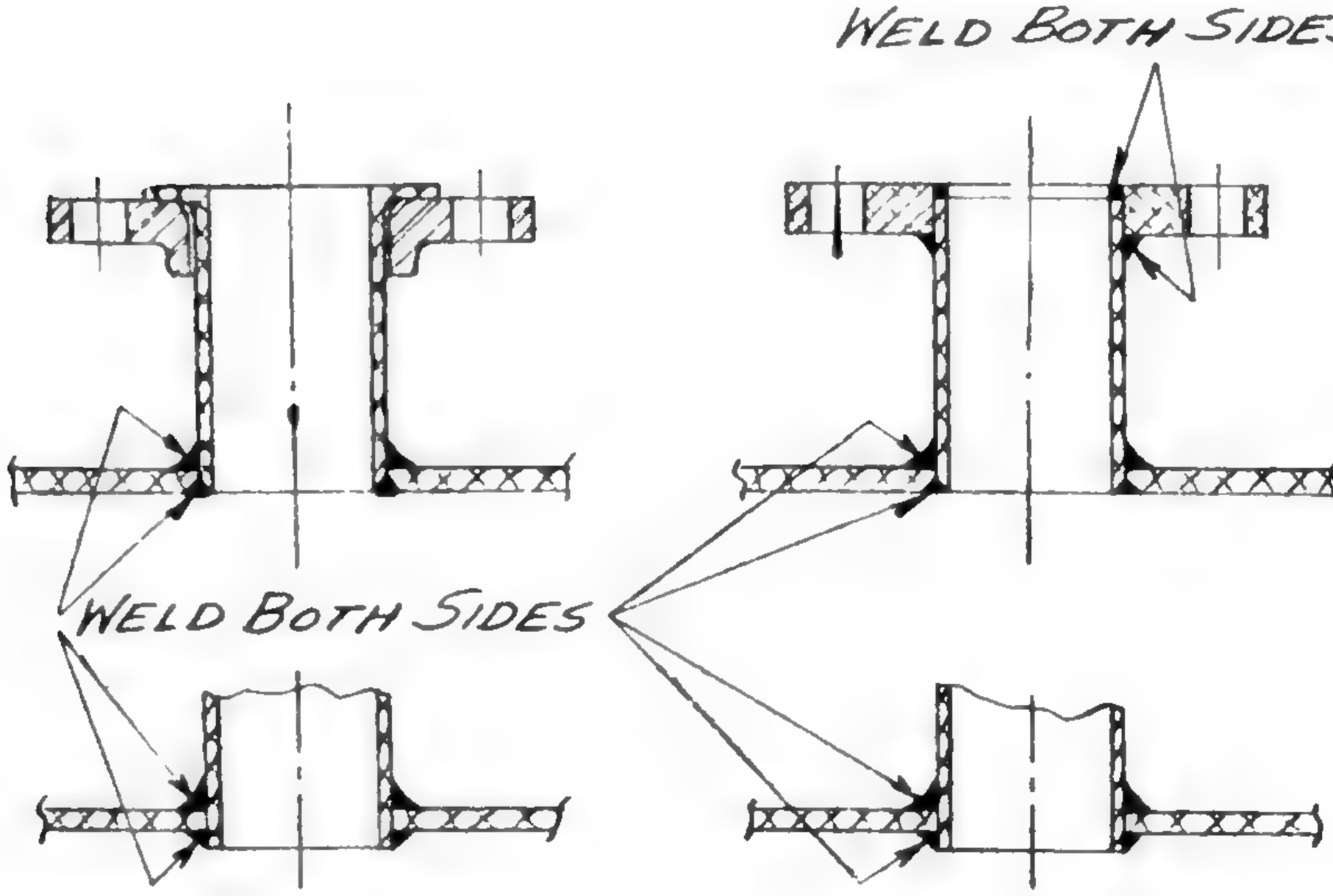


VAN STONE JOINT — ALUMINUM FIXED FLANGE

For tanks with sidewalls 3/16" thick or over, the minimum I.P.S. tube for which the tank can be flanged for butt welding to fitting is shown in the table below

MINIMUM I. P. S.	1"	2"	4"	6"
T	3/16"	1/4"	3/8"	1/2"

Fig. 3.—Typical Tubular Connections



VAN STONE JOINT — ALUMINUM FIXED FLANGE

Fig. 4.—Typical Tubular Connections Where Sidewalls Are Too Heavy for Flanging

of torches, hose and regulators is suitable for welding the aluminum alloys. (See Chapter 4.) Some work has also been done with oxy-natural gas and oxy-propane derivatives, and while good soundness and strength have been obtained, the use of these gases does not appear to be economical because of the comparatively low rate of welding.

Gas welding is suitable for welding material from about 0.040 up to 1 in. thick. Material heavier than 1 in. is not usually gas welded as the rate of heat dissipation in the part is so rapid that it is difficult to apply sufficient heat to melt the metal with a torch. Table 7 shows approximate equipment size for various thicknesses of material. The filler metal is very fluid when gas welding and the freezing rate is slow compared with arc welding. It follows that welding should be done in the flat position as it is very difficult to control a weld pool in the horizontal or vertical position and impossible to make other than a very short or a repair weld in the overhead position.

It is essential that the sheet or plate edges be properly prepared if sound welds of maximum strength are to be attained. Edge preparation for various thicknesses of material is shown in Fig. 5. Proper alignment of abutting edges is important in controlling distortion. This can be done best by tack welding at frequent intervals along the seam. On material up to $^1/_{16}$-in. thick, tack welds are placed from 1 to 2 in. apart, depending upon the length of the seam. This spacing can be increased proportionately up to a spacing of about 10 in. on material $^1/_2$-in. thick and heavier. Data for welding tanks are shown in Table 8.

Arc Welding

All of the arc-welding processes are useful for welding castings. These include shielded metal-arc, inert-gas metal-arc, carbon-arc and atomic hydrogen welding. The soundest and densest weld structure is obtained with the inert-gas metal-arc and carbon-arc processes. Complete removal of sand or other foreign material by chipping or other mechanical means is required when such welding is done. The presence of even small quantities of foreign material at the weld would interfere with the welding operation more seriously with these processes than with the shielded metal-arc or atomic hydrogen processes.

Shielded Metal-Arc Welding

Aluminum and the aluminum alloys can be welded with the shielded metal-arc. The highly concentrated heated zone obtained with the arc prevents excessive expansion of the parts being welded with consequent lessening of distortion. In addition, the preparation of the joints for welding is simpler and the rate of welding is faster than for other welding processes.

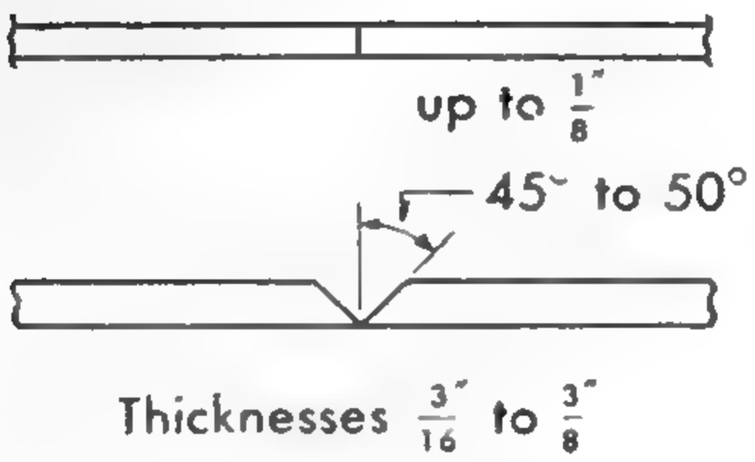
Because of the relative difficulty of controlling the arc, however, it is not practicable to weld a butt joint in material lighter than 0.081-in. thick, or fillet welds on plate lighter than $^1/_8$-in. thick. While shielded metal-arc welded joints are equal in strength to gas-welded joints, it is difficult to obtain liquid or gas-tight joints in material lighter than $^1/_4$-in. thick.

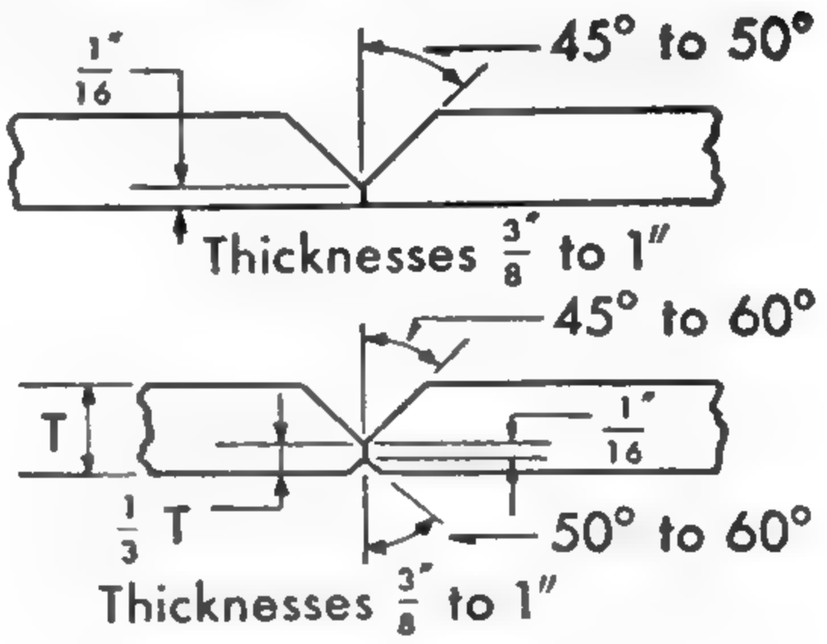
Metal-arc welds can be made with standard d.c. motor generator sets used for welding other metals. The proper polarity to be used should be determined by trial on the joints to be made. The capacity of the equipment and the electrode size are determined by the thickness of the material to be welded. Table 9 provides approximate machine settings and electrode sizes for welding various thicknesses of aluminum. No suitable electrode has been developed for welding the aluminum alloys with alternating current.

Electrode.—Unless a suitable flux is provided, the surface oxide present on the electrode core wire and the base metal will prevent coalescence of the weld metal. Consequently, successful results are obtained by using a covered electrode. As the 95% Al, 5% Si alloy provides superior fluidity at welding temperatures, this alloy is used for almost all of the commercially available electrodes.

Electrodes used in shielded metal-arc welding are coated with a welding flux that stabilizes the arc as well as removes the oxide coating. The presence of water in such coatings is a major cause of a porous weld structure and the coating must be thoroughly dry before use. Drying can be effected by heating the electrodes for several hours at 400 to 500°F. All of the flux mixtures are composed of hygroscopic salts that will pick up

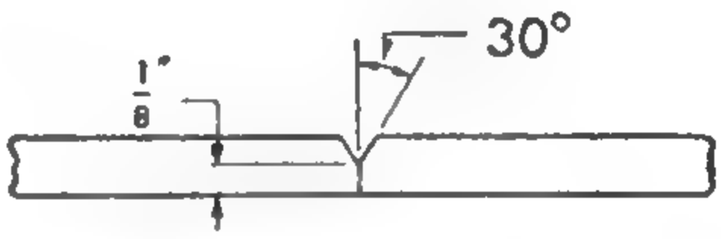
OXYHYDROGEN, OXYACETYLENE ATOMIC HYDROGEN, CARBON ARC

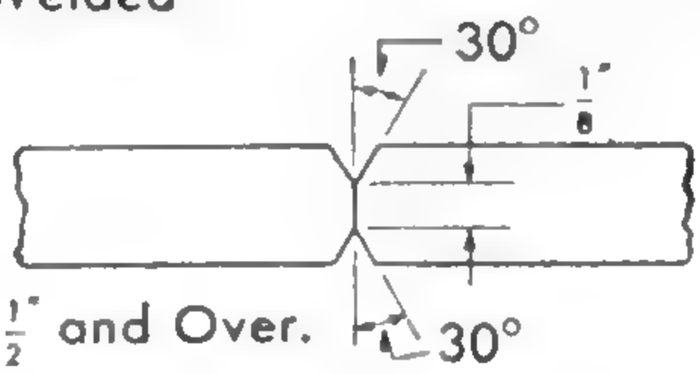




METAL ARC

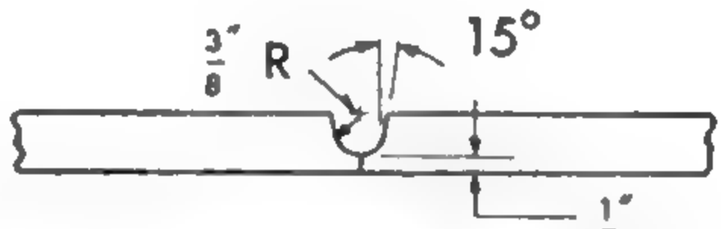
Thicknesses 1/2" Welded
From Both Sides.

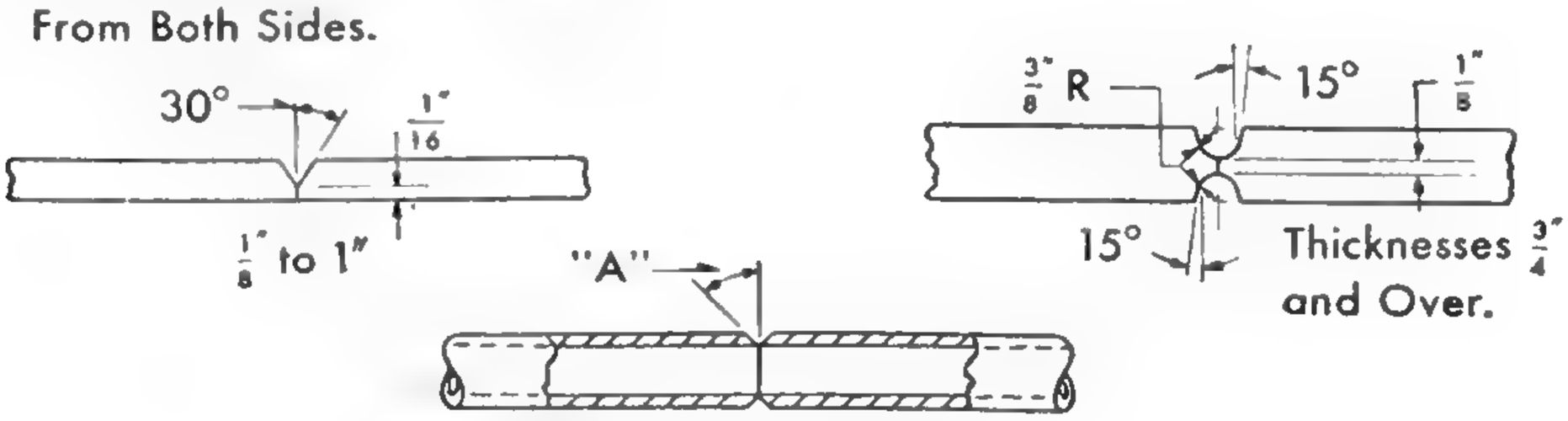




INERT GAS

Thicknesses up to 1/4" Welded
From Both Sides.





Pipe Welds up to 12" I.P.S.
A = 55° Posltion Weld.
A = 30° Roll Weld.

Fig. 5.—Typical Edge Preparations for Welding

moisture when exposed to the atmosphere. Deterioration of electrodes occurs on exposure to the atmosphere. Such deterioration can occur within a few hours under conditions of high relative humidity. In view of this, it is desirable to store electrodes in a dry location and, in addition, to apply a drying operation as described above before the electrodes are used. (See Chapter 10 for further information on Shielded Metal-Arc Welding.)

Inert-Gas Metal-Arc Welding

A major factor in the expanded use of welded construction in the aluminum alloys has been the adoption of the inert-gas metal-arc welding process for these materials. The process is superior to the gas and other arc-welding processes for welding aluminum in several respects. The soundness, strength, and leak tightness of welds made by this process are better on the average than for welds made with the other processes. Welding flux is eliminated; consequently, the possibility of corrosive attack from inadequate flux removal is not present. Another important factor is that welding in either the vertical or overhead position can be accomplished with almost the same facility and with equal soundness and strength as welds made in the flat position. Finally, the process can be adapted to mechanized welding more easily than the other welding processes.

Welding of the aluminum alloys is usually accomplished with alternating current, argon gas and a tungsten electrode. Helium gas of adequate purity, when available, is sometimes used. Most equipment is provided with a high frequency circuit superimposed on the welding circuit to insure the maintenance of the welding arc. Equally good results are obtained with equipment arranged so that the high frequency current flows whenever the welding arc is established or is used only for a few cycles to initiate the arc and to automatically re-establish it if the arc is extinguished for any reason. Filler metal is applied in much the same manner as for gas welding. Equipment capacity and machine settings vary with the thickness of material being welded. Table 10 shows machine settings that have been found suitable for the usual commercial requirements.

Manual welding operations can be accomplished commercially on material as thin as 0.040 in. Material up to $2^1/_2$-in. thick has been butt welded and even heavier material can be welded. Precleaning of the metal prior to welding is desirable to obtain maximum welding speed, although much welding on the nonheat-treatable alloys is done without precleaning other than to remove grease or dirt. When welding heat-treatable alloys or parts that have been severely formed or subjected to heating operations for annealing or hot forming, the surface of the metal at the joint should be cleaned to remove the oxide coating. In most cases, this is accomplished mechanically by wire brushing or by rubbing with steel wool. Chemical cleaning of the same type as used for spot welding is also very satisfactory.

Standard a.c. welding transformers with an open-circuit voltage of 60 to 100 are used for this work. Arc stabilization is obtained by superimposing a high frequency circuit on the welding circuit.

Machine welding is used where production justifies the tooling cost. There are contour applications and many types of joints which cannot be firmly jigged to prevent warping. For this type of work it is difficult to provide a machine with a mechanical contour follower to maintain the arc length within plus or minus 0.005 in., which is required for quality welding. Equipment with electronic arc length control has been developed to fulfill these requirements. There are many applications where a manually-adjustable machine will suffice where quite close operator supervision can be provided. Automatic filler metal feed is also available with either unit.

The cost of welding by this process is comparable with that of other welding processes used on the aluminum materials. The cost of argon gas is a major factor and it is essential to use a minimum quantity. The gas can be conserved by using as small an electrode and gas cup as possible to secure adequate coverage. Gas consumption increases slightly with increased welding speed, but is not proportional to the speed. It follows that mechanization of the welding operation to increase welding rates is frequently more desirable with inert-gas metal-arc welding than with other processes. For similar reasons, edge prepa-

ration for welding the thicker materials with a minimum amount of filler metal commensurate with getting complete penetration is an important factor. Suggested edge preparation for various welding thicknesses is shown in Fig. 5. (See Chapter 13 for further information on inert-gas metal-arc welding.)

Atomic Hydrogen Welding

Atomic hydrogen welding can be used for assembling aluminum parts. Good results have been obtained from the standpoint of soundness and strength of welds in the aluminum alloys with both manual and automatic atomic hydrogen welding equipment.

As this process involves an arc that is formed between electrodes in a torch, it is possible to control the heated zone on the parts being welded by moving the torch away from or toward the work. Filler metal is applied manually in much the same manner as when gas welding. Consequently, the process combines some of the flexibility of the gas welding operations with the concentrated heated zone approaching that of metal or carbon-arc welding. It is possible with atomic hydrogen welding to make fillet welds on an alloy such as 52S with little difficulty from cracking or overheating of the parts being welded.

Fluxing.—Atomic hydrogen welding is usually performed with standard gas welding flux. Both sides of the joint are painted with a water mixture of the flux and the welding rod is dipped in the mixture prior to welding. The technique of welding resembles the gas welding technique and requires some practice in order that the operator become adept at holding the arc and controlling the weld puddle. Butt welds can be made in material from $^1/_{16}$ up to $^3/_8$-in. thick and heavier. Approximate values for current settings and welding rod sizes are shown in Table 12.

The effect of the welding heat on the flux is more severe than when gas welding, and after the joint solidifies, a heavier scum than usual is present on the surface. This will interfere with laying down subsequent weld beads and removal of the flux deposit is usually required where more than one weld bead is used to make the joint.

Edge preparation prior to welding and the removal of welding flux after welding are accomplished by the same methods already described for gas-welded joints, Fig. 5. (See Chapter 11 for further information on atomic hydrogen welding.)

Carbon-Arc Welding

The use of the carbon-arc process for welding aluminum has recently increased. The reason for this is that sound welds, comparable in structure and appearance to gas welds, can be made with substantially less distortion in the parts. Both manual and automatic methods are used.

The technique for the manual method is similar to that used for other metals. A flux-coated welding rod is used to supply filler material. Improved welding speed and appearance will result with a welding rod covered with a thinner coating than that on the standard metal-arc electrode, although the latter is frequently used for filler material. Material $^1/_{16}$-in. up to about $^3/_8$-in. thick is welded commercially. Joint preparation is similar to that used for gas welding. Rod size and welding current as shown in Table 9 for shielded metal-arc welding are also approximately correct for manual carbon-arc welding.

This process has also been adapted to automatic equipment where the quantity of welding justifies the initial cost. Such installations have been used commercially for assembling aluminum alloy tank cars, and increased use of the process is anticipated on welded tanks for chemicals, gasoline, breweries and other applications of a similar nature.

Standard automatic equipment with a superimposed a.c. field to control the arc is used for this work. Data on machine settings, filler material and flux are shown in Table 11. This information applies to butt joints and represents average conditions. Some adjustments of the variables shown must necessarily be made on individual jobs, although the information is suitable for all of the weldable aluminum alloys.

No edge preparation is required on butt joints other than fitting the parts so that the abutting edges meet uniformly along a straight line. Use of a backing is essential and this is usually a $^1/_4$-in. thick, or thicker, copper bar with a $^1/_{16}$-in. deep by $^3/_8$-in. wide groove placed directly below the joint. Metal-arc tack welds or clamping devices are used to hold the edges in alignment.

Flux and Filler Metal.—Powdered flux is fed on the joint automatically and there are several good fluxes available for this purpose. Filler metal is also fed automatically. The same alloys used for gas welding can be used for this process, although hard-drawn rather than annealed wire will feed uniformly through the wire feeder. Commercially pure aluminum and aluminum-manganese alloy are welded with 99% aluminum wire and other alloys with 5% silicon-aluminum alloy wire. The diameter used depends on the thickness of the material welded, as shown in Table 11.

The same precautions for the removal of welding flux should be followed as are outlined for gas welding. Weld dressing after cleaning can also be handled in the same manner. (See Chapter 9 for further information on carbon arc welding.)

Brazing

Brazing aluminum materials differs from welding only in that special aluminum alloys having a lower melting point than that of the base metal are used for filler metal. Special fluxes, filler metal and techniques have been developed for brazing commercially pure aluminum, aluminum-manganese alloys and the aluminum - magnesium - silicon alloys. Techniques and filler metals have not been developed for commercially brazing the aluminum-copper, aluminum-zinc or the aluminum-silicon cast or wrought materials.

Three brazing processes are used: furnace brazing, dip brazing and torch brazing. Furnace brazing is done by applying a flux and preplaced filler metal, assembling the parts, and raising the temperature of the entire assembly or a batch of assemblies in a furnace to a point where the filler metal melts and flows into the joint, but without melting the base metal. Dip brazing is done by assembling the parts and dipping the entire assembly into a bath of molten flux held at a temperature above the melting point of the filler material, but below the melting point of the base metal. Torch brazing is done by dipping the filler metal in a flux and melting it into the joint with a torch.

Lock seam, tee, line contact or lap joints rather than butt or scarf joints are generally used. However, in making any kind of a joint, clearance between the parts is necessary for the flow of the filler metal. This flow depends on gravity and capillary attraction, so pressed or tight fits in assembling the parts must be avoided. Clearances of 0.006 to 0.010 in. are suitable for laps less than $^{1}/_{4}$ in. long; clearances up to 0.025 in. are used for longer laps. The correct clearance for any given joint is best determined by trial.

Joint design should permit easy assembly of the parts prior to brazing, and closed assemblies should be designed to provide for the escape of gases during brazing. The use of jigs and fixtures for holding the parts in alignment, particularly if of steel or stainless steel, is not usually feasible. The difference in thermal expansion between steel and aluminum in most cases will force the parts out of line. Aluminum fixtures are satisfactory only if made from an alloy that will not melt at the brazing temperatures and so shaped that there is no contact between the fixture and the molten brazing flux and filler metal. In most applications, it has been found desirable to design the parts to be self jigging or held in alignment by rivets or projections that remain on the part after brazing.

Materials.—Brazing aluminum alloys differs from brazing other metals in that the filler metal is an aluminum alloy rather than a silver or copper-base alloy, of suitable composition so that the melting point is lower than the parent material's. This is accomplished practically by alloying aluminum with varying amounts of silicon, or copper and silicon, as shown in Table 13.

It has been found practicable also to apply some of these brazing alloys as an integral coating on one or both sides of certain aluminum alloy sheet materials. This product, known as brazing sheet, is convenient to use in that parts can be formed by drawing, bending, spinning or any of the usual shop procedures without injury to the coating of filler metal. The parts are then assembled, flux is applied, and brazed by raising to a temperature sufficient to flow the coating of brazing filler metal. The use of these materials has been found economical because no additional filler metal in the form of wire or shims need be applied.

Brazing sheet is produced commercially

with a coating of Al–7.5% Si alloy. This material is brazed at a temperature from 1120 to 1140°F. Brazing sheet is also produced with the same coating on aluminum-magnesium-silicon alloy that is heat treatable. Parts made from this material can frequently be quenched in a water spray or air blast on removal from the brazing furnace with the result that higher strength is obtained. For example, a part made from the Al-Mn brazing sheet has a typical tensile strength of 15,000 psi. while a part made from the Mg-Si aluminum alloy in the solution-heat-treated and precipitation-hardened temper has a typical tensile strength of 35,000 psi.

Not all of the aluminum alloys can be brazed. Materials shown in Table 5 with a melting point higher than that of the filler metals shown in Table 13 can be brazed. Commercially pure aluminum and Al-Mn alloys can be brazed with any of the filler materials. The Al-Mg-Si alloys are brazed with Al-Si-Cu filler metal. Any of the commercial forms of the wrought alloys, such as sheet, tubing, forgings and extruded shapes, are suitable for brazing. None of the standard casting alloys are suitable for brazed construction. There are a number of experimental materials, however, that show promise for this purpose and communication with the manufacturer of aluminum castings is suggested where the brazing of cast parts seems to be desirable.

Furnace Brazing.—Brazing operations are performed in standard types of furnace equipment. Temperature regulation within ±5° F. of the nominal temperature is necessary to secure consistent results. This requires automatic temperature control. For most parts circulation of the furnace atmosphere is not essential to the brazing operation but is a desirable feature in furnace construction in that it reduces the heating time and results in more uniform distribution of temperature in the furnace. If the parts that are to be brazed are crowded into passages too small in area to permit uniform temperature rise by the natural convection currents in the furnace, forced circulation is absolutely essential.

The total time brazed parts are exposed to the furnace temperature depends on the thickness of the parts. Experience indicates that furnace-brazed parts can be made from 0.006 up to $^1/_8$-in. thick. Material 0.006-in. thick will reach brazing temperature in a few minutes, while it requires 40 to 45 min. for $^1/_8$-in. thick material to reach temperature. A period of from 2 to 6 min. after the metal reaches the brazing temperature is required to melt the brazing alloy and flow it into the joints. Time for any specific job is determined by trial. In this connection it should be noted that because of the varying rates of temperature rise, it is not good practice to design an assembly with many variations in the thicknesses of individual parts.

The brazing temperature is adjusted to suit the alloy being brazed. In the case of aluminum-manganese parts, a temperature between 1160 and 1185°F. is used. Aluminum-magnesium-silicon alloys are brazed at 1060 to 1090°F. The correct temperature for a specific job is determined by trial and will depend on the design of the part and the size of the fillets required. Larger fillets are obtained at the upper end of the temperature range. In determining the correct temperature it is desirable to measure actual temperature of the parts (load temperature) by attaching a thermocouple to one of the parts.

Torch Brazing.—Torch brazing differs from furnace brazing in that the heat is applied locally with a welding torch. Oxy-hydrogen, oxy-acetylene and oxy-natural gas have been used for this purpose. The brazing flux is mixed with water and applied to the brazing alloy by dipping. Heat is applied to the part until the temperature reaches a point where the flux and the filler metal melt and wet the surfaces of the base metal with little or no melting of the base metal itself. The process resembles gas welding except that the filler material is more fluid and will flow into a lap joint. The speed of making the joint is also more rapid.

Dip Brazing.—Dip brazing differs from furnace brazing in that it is not necessary to apply the brazing flux in a separate operation. In dip brazing, the parts are assembled with the filler material in place. The assembly is placed on a suitable rack and dipped in molten flux held at the proper temperature to melt the filler material and produce its flow into the joint but yet not melt the base metal parts. While commercial experience is limited, its field of possible applications includes

finned tubing, radiators, heat exchangers and similar assemblies that permit complete drainage of the molten flux after brazing.

Parts are prepared for dip brazing in much the same manner as for furnace brazing from the standpoint of cleaning and assembly. Dip-brazed parts should be designed so that alignment during brazing is obtained by the fit of the parts rather than by holding the pieces in jigs or fixtures. For example, in brazing tubes to header plates, a close fit at the joint can be obtained by expanding the ends of the tubes into the holes in the header plate. Racks for suspending the parts in the flux are usually made from nickel or pure aluminum wire. Cast iron, stainless steel and nickel alloy racks have also been used, although there may be some contamination of the bath with these materials.

The same temperature range used for furnace brazing is suitable, with the final temperature chosen by trial. The parts are dipped from 30 sec. to 3 min., depending on the shape and thickness.

Increased speed and smoother joints are obtained if the parts are preheated to between 900 and 1000°F. before dipping in molten flux. This is usually accomplished in a separate operation and prevents local freezing, distortion, inconsistent joining and entrapment of flux in small openings in the pieces.

It is important that the flux be held in a container which will not cause contamination. Pure nickel pots have been found satisfactory from this standpoint and a service life of about six months can be expected with this material. Some ceramic pot linings are suitable, although unless previous experience has indicated a ceramic is not attacked by the flux, preliminary tests should be made. Both external gas-fired heating and electric-resistance heating of the molten flux have been found satisfactory. Temperature control within ±5°F. of the brazing temperature is essential. The size of the pot also should be such that the chilling effect from dipping the parts to be brazed does not drop the temperature below this tolerance.

The addition of flux to replace drag-out or increase the depth will introduce moisture. The same conditions exist when a fresh batch of flux is melted. The source of this water is the chemically combined water in the flux constituents and the effect is to attack the aluminum parts unless the bath is dehydrated. Dehydration is accomplished by dipping a coil or piece of aluminum sheet in the flux. As long as moisture is present, hydrogen is evolved which ignites on the surface, producing small orange flames.

Cleaning Joints After Brazing.—It is *always* necessary to clean the joint after a brazing operation. Many parts can be immersed in boiling water before cooling from the brazing temperature, which will remove the major portion of the flux. If such a quench distorts the part, it should be allowed to cool in air before it is immersed in boiling water.

This is followed by a dip in concentrated nitric acid for 5 to 15 min., depending on the design of the parts. The acid is removed with a water rinse, preferably in boiling water in order to accelerate drying. An alternative cleaning method is to dip the part for 5 to 10 min. in a 10% nitric plus 0.25%hydrofluoric acid solution at room temperature. This in turn is followed by a water rinse.

Brazed parts with thin sections (0.010-in. and lighter) and parts where maximum resistance to corrosion is important, should be immersed in hot water followed by a dip in a solution of 10% nitric acid and 10% sodium dichromate for 5 to 10 min. This in turn is followed by a hot water rinse. (See Chapter 22 for further information on Brazing.)

Spot Welding

All of the commercial aluminum alloys may be spot welded provided the thicknesses involved are not too great. The provision of proper equipment for making the welds, the preparation of the surface of the material for welding and the use of correct machine settings are necessary to produce satisfactory welds.

Aluminum and aluminum alloys have comparatively high thermal and electrical conductivities, and in order to make a spot weld, high values of welding current and relatively short welding times are necessary. A further factor which influences the choice of equipment for spot welding aluminum is the softening of the material at the welding temperature which necessitates a slight movement of the welding electrode into the material being welded. While this movement is small, it must take place in a very short

time, perhaps 0.002 to 0.005 sec., and as a consequence, considerable acceleration of the welding electrode assembly is necessary if contact is to be maintained between the welding electrode and the material welded. For this reason, the moving electrode system should possess low inertia and should be so guided as to minimize friction.

A.C. Spot Welding.—One method in wide use is the alternating-current method wherein the high welding current is obtained from the secondary of a welding transformer having a turn ratio from 20:1 up to 100:1. The primary of the welding transformer is usually connected to either a 220- or 440-v., 60-cycle power supply, and suitable means are interposed between the power supply and the welding transformer to provide a range in time of application of welding current from one cycle up to thirty cycles. The secondary current required varies with the thickness of the material welded as listed in Table 14.

Current Demand.—One of the chief objections to alternating-current spot-welding machines is that the high currents for welding aluminum place a very high electrical demand upon the system supplying the welding machine. This current demand is of intermittent nature, single-phase, and of very low power factor, and may disturb other electrical equipment, for example, causing blinking of lights. This condition may be alleviated to a large extent by the installation of static condensers in series with the primary of the welding transformer. The manufacturer of the welding equipment should be consulted in connection with the proper size and number of condensers required.

Stored Energy Method.—The electrical demand for spot welding aluminum may also be reduced by the use of several types of stored energy welding equipment.

Table 15 shows welding conditions for spot welding Alclad 24S-T aluminum alloy with electromagnetic and condenser-discharge equipment. Alloys having higher surface hardnesses generally require higher values of electrode force for best results.

Electrodes.—The proper choice of electrode shape and the maintenance of this shape in production are essential to obtain consistent spot welds on aluminum. The welding electrode serves as a means of conducting the welding current into the parts being welded, exerting sufficient pressure on the material to hold it in place while the weld is made, and of conducting the heat out of the parts welded to prevent the weld zone from reaching the outside surfaces of the material. At least one of the electrodes must be of such shape that a high concentration of current will be obtained in the weld. Electrodes machined to a spherical radius on one or both sides of the work are used for most welding operations. Consistent strength and size of weld can be obtained by refinishing the electrodes periodically with a tool contoured to the proper radius and faced with a fine abrasive cloth. The best tip radius varies with the thickness of the metal and suggested values are shown in Table 16.

It is essential that electrodes be made from a material having high hardness and high electrical and thermal conductivity. A number of copper alloys having hardnesses greater than Rockwell B-65, and electrical conductivities greater than 75% of that of pure copper, are used (RWMA Class 1 or Class 2, Group A). Hard-drawn copper electrodes of conical or dome shape will not maintain their shape in production welding and their use is to be avoided.

The electrodes must be of sufficient diameter to carry the welding currents used without undue heating. A $^{5}/_{8}$-in. diam. electrode is suitable for currents up to 35,000 amp. and a welding time of 15 cycles when the rate of welding is not more than 40 welds per minute. Where higher welding currents or greater welding speeds are used, $^{7}/_{8}$ or $1^{1}/_{4}$-in. diam. electrodes should be used. For welding currents less than 20,000 amp. and welding times less than 8 cycles, $^{1}/_{2}$-in. diam. electrodes are satisfactory.

The electrodes must be water cooled by a stream directed through the end of the electrode cooling-water hole. This hole should extend to within $^{3}/_{8}$ in. of the welding face. A water flow of one or more gal. per min. should be maintained through the electrode.

With continued welding, a coating of aluminum alloy forms over the face of the electrode. This aluminum alloy is of low electrical conductivity and continued welding with it on the electrode surface soon results in sticking of the electrodes

to the work and melting of the surface of the material welded. This *pickup* may be removed by dressing the electrodes with a fine grade of abrasive cloth. In dressing dome-shaped electrodes to remove pickup care should be taken to maintain the original electrode shape.

Pickup in stored energy welding machines may be minimized by reversing the direction of current flow through the electrodes on successive welds. Excessive electrode pickup is generally the result of improper surface preparation of the material prior to welding, insufficient electrode force or excessive welding current. Refrigeration of the welding electrodes may result in increased electrode life if good welding conditions are employed. To make the most effective use of the cooling effect of the refrigerant, the distance from the face of the electrode to the coolant should be $^3/_8$ in. or less, and the inside cooling surfaces of the electrode fluted to aid in streamlining the flow of coolant.

Surface Preparation.—Aluminum alloys are characterized by a rather heavy oxide coating, and while welding may sometimes be performed without removing or altering this coating, better quality welds and more economical welding will result if both surfaces of the material are cleaned prior to welding. The surfaces of aluminum alloys may be prepared for spot welding either by mechanical or chemical methods. Mechanical methods of surface preparation are employed where the volume of production spot welding is small or where the size of the assemblies does not permit the handling necessary for chemical methods of surface preparation.

Mechanical surface preparation may be performed with a fine grade of abrasive cloth, fine steel wool or a fine motor-driven scratch brush. Chemical surface preparation consists of cleaning the parts in an alkaline or a vapor degreaser, treating in one of several available oxide removal solutions, rinsing in cold fresh water and drying. A second rinse in boiling water may be employed to facilitate the drying. There are a number of chemical cleaning solutions available commercially, especially designed for preparing aluminum for spot welding, which are applied in accordance with the recommendations of the manufacturers of these materials.

A simple, room-temperature, chemical surface-treating solution which works satisfactorily for most aluminum alloys consists of 1.5 to 3.0% by volume of 28% hydrofluosilicic acid, H_2SiF_6, and 0.1% by weight of a wetting agent to insure intimate contact of the etchant and the metal surface. An immersion time of 5 to 10 min. is generally employed. Certain alloys such as 14S, 17S, 24S, 61S and R361 which do not respond to this treatment may be satisfactorily prepared by a 10-min. immersion at 180°F. in a 2% solution by volume of nitric acid, HNO_3, containing 0.2% by weight of a wetting agent.

Another economical method of preparing the surface for spot welding is to degrease the material and etch the surface in a 10% nitric acid, HNO_3, 0.25% hydrofluoric acid, HF, solution. This is followed by a cold water rinse and occasionally an additional hot water rinse to promote fast drying. Most materials are immersed in the mixed acids for 5 min. although this time can be varied to suit the requirements of the work.

The maintenance of chemical treating solutions at the proper strength is necessary to insure satisfactory preparation of the surfaces for spot welding. The acid strength of treating solutions may generally be determined by titration and adjusted accordingly. Once these solutions have been placed in use, however, there are factors which may operate to influence their action, and the aluminum may not be properly prepared for spot welding although the solutions are at the proper acid strength. Therefore, the method of controlling the solutions by measuring the surface resistance after treatment of small coupons of the alloy being welded is suggested. Additions are made to the solution as required to maintain the surface resistance of the control samples at a desired low value.

Shop Practices.—In order to set up the welding machine to produce satisfactory spot welds, the production of sample welds is necessary. A series of welds should be made on sample stock of the same gage, alloy, surface condition and spot spacing as the job to be welded. These specimens are torn apart by driving a chisel in between the sheets and in between the welds or by a *peel* test. Each spot weld should pull a button of diameter equal to twice the thickness of

the material, plus $^1/_{16}$ inch. If the spot diameter is too small, it may be increased by increasing the welding current. If expulsion of metal from the weld between the sheets is occurring the welding pressure should be increased or the current reduced. If the outside surfaces of the sheet exhibit evidence of excessive darkening or surface melting, or of sticking to the electrodes after only one or two welds have been made, either the pressure should be increased or the current decreased.

Spot welds in aluminum alloys 17S, 24S, 75S and R301 in either bare or clad form will not always pull buttons* all the way through the sheet when the thickness of material is greater than 0.080 inch. In these materials, the weld is tested as above and the diameter of the fractured area determined.

When welding unequal thicknesses of materials, the thickness of the thinner material governs the machine setting and the diameter of the weld. Where more than two thicknesses are welded, the setting is governed by the outside sheets using values of welding current and welding pressure slightly higher than normal. If expulsion of metal between the sheets cannot be entirely eliminated by changing the machine settings, a more thorough method of cleaning the material should be adopted. A light rub of the material with fine steel wool just before welding will often help this condition.

Spot welds in Alclad or Pureclad 24S-T and Alclad 75S-T are subject to cracking if too high a value of welding current or too low a value of welding pressure is used, or if the material is not cleaned sufficiently. These cracks may be eliminated or reduced to some extent by using a larger radius on the domed electrodes or by dressing a small flat spot not greater than 2T plus $^1/_{16}$ in. in diameter on the domed or cone tip (*T* equals thickness of material). This flat spot reduces the indentation of the electrode into the sheet and results in maintaining more uniform pressure during the weld.

Strength of Welds.—Spot welds are usually designed to carry shear loads. The strength of the welds will vary to a considerable extent with the alloy welded, the thickness of the material welded and the machine settings used in making the welds. Minimum values of shear strength for various thicknesses and alloys are given in Table 17. The production of welds of small size and of lower strength than listed in Table 17 is to be avoided since settings which give small diameter welds in aluminum are apt under production conditions to produce no weld at all.

While spot welds are not usually designed to carry tension loading, such loading often exists in the form of secondary stress. The tensile strength of spot welds will vary from 20 to 90% of the shear strength and where it is important that such strengths be known, special tests should be made.

Resistance to Corrosion.—Spot welds in aluminum alloys 2S, 3S, 52S, 61S, R353 and R361 are not selectively attacked by corrosion and spot-welded structures of these materials can be expected to give the same service as the unwelded material. Spot welds in the cladded forms of 24S, 75S and R301 are protected from corrosion by the clad coatings on the sheet, even if the weld extends through the coating. Best resistance to corrosion is obtained when the weld does not extend through the coating. Spot welds in 17S and 24S aluminum alloys may be selectively attacked under severe corrosion conditions. For this reason, spot-welded 17S and 24S construction is to be avoided where corrosion is a factor. If the joint can be protected by paint, particularly in the faying surfaces, some protection of the spot welds is obtained. When 17S or 24S is spot welded to the cladded forms of 24S or R301, the coating on the clad material will protect the uncoated material to some extent. However, in time the clad coating will be used up and corrosion of the spot weld will ensue.

Seam Welding

Seam-welding equipment for welding aluminum is similar to spot-welding equipment except that the electrodes are replaced by roller electrodes from $^3/_8$ to $^5/_8$-in. thick and from 6 to 9 in. in diameter. One or both of these wheels are dressed to 158- to 166-deg. included angle vee or a 1 to 2 in. radius to concentrate the current in the weld. The wheels are

* That part of the weld which tears out including all or part of the nugget.

cooled internally or the wheels and the work are cooled by a generous flow of water directed against the periphery of the wheel near the weld. Usually one of the wheels is driven at an adjustable speed from one to five feet per minute.

It is essential for alternating-current seam welding that the welding timer initiate and cut off the current in synchronism with the supply voltage. Electronically controlled timing equipment is the only satisfactory means available for doing this with sufficient accuracy to produce uniform welds in aluminum. Pressure-tight welds are made by producing a series of overlapping spot welds. The current is cut on and off by the electronic timer, one weld being made for each *on* application of current. The speed of the rolls, together with the *on* plus *off* time, is adjusted so as to get the number of spots per inch shown in Table 18. A number of combinations of cycles *on* and cycles *off* may be used, although the ratio of *on* time to *off* time should be from one-fifth to one-third.

Welding pressure and welding current are adjusted to produce the desired width of weld, which should be about twice the thickness of the material welded plus $^1/_{16}$ in., and the desired surface condition. Poor surface condition may be improved by either increasing the welding pressures or decreasing the welding current. Excessive welding speed will result in sticking of the work to the welding wheel and can be corrected by increasing the *on* plus *off* time, and decreasing the roll speed to give the desired spots per inch. Where a continuous pressure-tight weld is not required, the seam-welding machine may be used to place spot welds at any uniform spacing from about $^3/_8$ to 2 inches. The welding *on* plus *off* time is set at from 20 to 60 cycles with the *on* time about one-half of the value recommended in Table 14 for spot welding. The roller speed is adjusted to give the desired spot spacing. In this case, the speed of welding will be from 60 to 180 spots per minute.

As in spot welding, aluminum sticks to the electrodes, so in seam welding it adheres to the rollers and must be removed by dressing the wheel with a suitable grade of abrasive cloth. A moderately coarse grade of cloth is used so as to produce a rough surface on the wheel which prevents slipping between the wheel and the work. On continuous seam welding, the wheels must be cleaned after three to five revolutions, and on intermittent welding after from 10 to 20 revolutions of the wheel. Continuous dressing of the electrode may be performed using a medium fine grade of commutator stone held against the wheel with 5 to 10 lb. of pressure. Typical settings for seam welding aluminum alloy 52S-H14 are given in Table 18. This table may also be used as a basis for seam welding other alloys, appropriate changes being made in the pressure and the current to produce the desired width of weld.

Flash Welding

All aluminum alloys may be joined by the flash-welding process. Joints of higher quality can be obtained by welding any particular alloy in the hard temper rather than welding it in the soft temper and hardening by subsequent heat treatment or work hardening. In this process, the parts to be welded are held in suitable dies of the flash-welding machine. The parts are driven together with an accelerated motion at the same time voltage from the secondary of the welding transformer is maintained on the parts. As the approaching parts make contact, local short circuits occur which cause rapid melting and expulsion of metal. This violent flashing action, lasting from one-half to one and one-half seconds, prepares the metal surfaces for joining and produces the required heat gradient in the parts to permit the desired upsetting. The flashing period is terminated by the nearly simultaneous cutting off of, or decrease in, the magnitude of the power and a sudden increase in the velocity of the moving die. The ends of the parts being welded are forced together and any molten metal or oxides remaining at the interface are squeezed out.

The process is particularly adapted to making butt or miter welds between aluminum sections. The process has also been adapted to joining aluminum and copper bars and tubing, and the joints so produced fail in the aluminum outside of the weld. If annealed aluminum is used to make the joints, the joints are not brittle.

Flash-welding machines of the alternating current and storage battery types are presently used on aluminum alloys. On machines of 75 kva. or lower capacity

platen motion is produced by direct mechanical drive. On machines of higher capacity platen motion is generally produced by a hydraulic system. A machine for flash welding aluminum should have a secondary current capacity of approximately 100,000 amp. per square inch of material to be welded. Secondary voltages from 2 to 18 volts have been used. The amount of material flashed off varies from $^1/_4$ to $^1/_2$ in., and the upset motion is equal to or greater than the flashing travel. The flashing time varies from 30 cycles for welds in small sections, such as $^1/_4$ to $^5/_{16}$-in. O.D. aluminum tubing, to 70 cycles for a $^1/_4 \times 2$-in. solid bar. The welding current is cut off or decreased in magnitude at the beginning of upset. The hot upsetting period ranges from 5 to 25 cycles in duration depending upon the alloy and area of section being welded.

WELDING CASTINGS

In general, the welding techniques for aluminum alloy castings are similar to those used on aluminum sheet and wrought sections. The susceptibility of many castings to thermal strains and cracks, because of their intricate design and varying section thicknesses, should be carefully considered. In addition, many castings in highly stressed structures depend upon heat treatment for their strength, and welding tends to destroy the effect of such initial heat treatments. Unless satisfactory facilities for reheat treatment are available, the welding of such heat-treated castings is not recommended.

Preparation.—When a broken aluminum casting is to be welded, it should first be cleaned carefully with a wire brush and gasoline to remove every trace of oil, grease and dirt. Unless the casting has a very heavy cross-section, it is not necessary to tool the crack or cut out a vee as this can generally be accomplished by means of the torch and puddling iron. It is necessary, however, that the material surrounding the defect be completely melted or cut away before proceeding with the weld. If a piece is broken out, it should be held in correct position by light iron bars and appropriate clamps. The clamps should be so attached that the casting will not be stressed during heating.

Preheating.—If the casting is large or has intricate sections, it should be preheated prior to welding to between 500 and 700°F. slowly and uniformly in a suitable furnace. If the casting is small, or if the weld is near the edge and in a thin-walled section, the casting may be preheated in the region of the weld by means of a torch flame. Cast aluminum should be heated slowly to avoid cracking in the section of the casting nearest the flame.

Broken pieces should be tack welded into place as soon as the casting has been preheated. Actual welding of the piece should commence at the middle of the break and then continue towards the ends. When the weld is finished, the excess molten metal should be scraped off with a puddling iron, and the casting allowed to cool slowly.

Technique.—Holes in castings are welded in much the same manner as are cracked and broken castings. It is necessary to melt away or cut away the sides of the hole in order to remove all pockets and to permit proper manipulation of the torch.

For welding ordinary castings, a 5% silicon or a 4% copper, 3% silicon aluminum alloy welding rod is generally used. However, in the case of heat-treated alloy castings, it is best to use a welding rod of the same alloy as the casting.

A flux should be used when welding aluminum castings. Puddling alone will merely break up the oxide film and leave it incorporated in the weld, while fluxing will cause the oxide particles to rise to the surface so that a clean, sound weld will result. It is important that the added metal be completely melted, and the molten metal thoroughly worked with the end of the welding rod or with a puddling iron. Thus, the flux and oxide are worked to the surface of the molten metal, and there is very little danger of contaminating the weld metal with particles of flux or other foreign inclusions.

In the welding of large castings in which the area to be welded is sufficiently large and easily accessible, the welding rod is often dispensed with, and molten metal added directly from a small ladle. By this practice of flow welding, the amount of porosity and oxide in the weld is reduced to a minimum, the tendency

for burning in the surrounding areas is lessened, and metal of the same analysis as the casting is used.

Flow welding is recommended for filling large holes and cracks. To accomplish this, a form or jig of fire clay, Plaster of Paris or metal is fitted around the hole or crack. After the casting has been preheated in a suitable furnace, the flux is brushed on the joint faces and the metal is brought up to the proper temperature by means of a torch. Molten metal, at not over 1300°F., is poured into the weld. The flux and absorbed oxide will immediately float to the surface and can be skimmed off.

Arc Welding.—The metal or carbon arc can also be used for the welding of castings. Of the two, the carbon arc is preferred as it produces welds free of oxide and porosity. Even with carbon-arc welding, castings in some cases must be preheated to prevent thermal cracks. The use of rods carefully coated with flux and the control of welding current are essential for good arc welds.

COMMON APPLICATIONS

Aluminum and its alloys are useful for a wide range of industrial and domestic applications by virtue of their varied characteristics and properties from resistance to atmospheric corrosion to strength in structural members.

These alloys find their major use and application in the following industries:

Aircraft
Automotive
Household Appliances
Structural
Marine
Architectural
Chemical and Dairy
Pressure Vessels
Railroads

Aircraft.—Probably their most extensive application, utilizing extruded shapes, tubing, sheet, castings and forgings; examples are aircraft pistons, impellers for superchargers and jet engines, engine crankcases, cylinder heads, and aircraft wings and fuselages. (See Chapter 55.)

Automotive.—Aluminum alloys have had extensive application of sheet, extrusions and castings; examples are tubing for fuel, oil and hydraulic lines, Diesel engine pistons, and crankcase and cylinder heads, and truck bodies. (See Chapter 54.)

Household Appliances.—These materials are extensively used for domestic cooking utensils; also for vacuum cleaners, washing machines, trim, doors and window framing.

Structural.—Increased use is being made of the readily-fabricated heat-treatable grades of these materials for load-carrying members and other structural shapes; extrusions for ornamental use as trim and fixtures; aluminum sheet for exterior wall covering, in addition to the Alclads, when increased strength is desired. (See Chapter 47.)

Marine.—These materials are used primarily for small craft use; also engines, instrument boxes, stateroom partitions and furniture, and for special-purpose applications. (See Chapter 52.)

Architectural.—The major applications of these materials are for ornamental use, doors, windows, moldings, and sheet wall covering.

Mining.—Applications of these materials to this field are as mine cars, skips, cages, car loaders, drills, jack posts, rail-benders, punches, surveying instruments, shovel dippers and dragline excavators.

Miscellaneous Applications.—These materials are also used for the following products and equipment:

Railroad tank cars
Pressure vessels
Storage tanks
Chemical and dairy tank cars
Electrical wire and cables
Overhead traveling cranes
Bridge floor systems

Table 1—Typical[a] Mechanical Properties of Wrought Aluminum Alloys[b]

ASTM No.	Commercial Designation	Temper	Tensile Strength, Psi.	Yield Strength (Offset = 0.2%), Psi	Elongation, % in 2 In. Sheet (1/16-in. Thick)	Elongation, % in 2 In. Round (1/2-in. Diam.)	Hardness, Bhn. 500-kg. Load	Shear Strength, Psi.	Endurance Limit,[c] Psi.
A2	2S	O	13,000	5,000	35	45	23	9,500	5,000
		H14	17,500	16,000	9	20	32	11,000	7,000
		H18	24,000	22,000	5	15	44	13,000	8,500
M1	3S	O	16,000	6,000	30	40	28	11,000	7,000
		H14	21,500	19,000	8	16	40	14,000	9,000
		H18	29,000	26,000	4	10	55	16,000	10,000
MG1	4S	O	27,000	10,000	20	25	45	16,000	14,000
		H34	34,000	27,000	9	12	63	18,000	15,000
		H38	40,000	34,000	5	6	77	21,000	16,000
CS41	14S	O	27,000	14,000	..	18	45	18,000	13,000
		T4	62,000	44,000	..	20	105	38,000	18,000
		T6	71,000	60,000	..	13	135	42,000	18,000
Clad CS41	Alclad 14S or Hardclad 301	O	25,000	14,000	21	..	...	18,000	.....
		T4	62,000[d]	37,000[d]	22	..	...	37,000	.....
		T6	68,000[d]	60,000[d]	11	..	...	41,000	.....
CM21	17S	O	26,000	10,000	..	22	45	18,000	13,000
		T4	62,000	40,000	..	22	105	38,000	18,000
CG21	24S	O	27,000	11,000	19	22	47	18,000	13,000
		T3	70,000	50,000	16	..	120	41,000	18,000
		T4	68,000[e]	48,000[e]	20	19	120	41,000	18,000
		T36	73,000	57,000	13	..	130	42,000	18,000
Clad CG21	Alclad 24S or Pureclad 24S	O	26,000	11,000	19	..	...	18,000	.....
		T3	64,000[f]	44,000[f]	15	..	...	40,000	.....
		T4	64,000[f]	42,000[f]	19	..	...	40,000	.....
		T36	67,000[f]	53,000[f]	11	..	...	41,000	.....
GR1	52S	O	27,000	12,000	25	30	45	18,000	17,000
		H34	37,000	31,000	10	14	67	21,000	18,000
		H38	41,000	36,000	7	8	85	24,000	19,000
GS22	53S or R353	O	16,000	7,000	..	35	26	11,000	8,000
		T4	33,000	20,000	..	30	65	20,000	13,000
		T5	30,000	25,000	..	13	65	18,000	.....
		T6	39,000	33,000	..	20	80	24,000	13,000
GS21	61S or R361	O	18,000	8,000	22	30	30	12,500	9,000
		T4	35,000	21,000	22	25	65	24,000	13,500
		T6	45,000	40,000	12	17	95	30,000	13,500
GS2	63S	F (as ext.)	22,000	13,000	20	..	42	14,000	.....
		T5	30,000	25,000	12	..	65	18,000	.....
		T6	35,000	30,000	12	..	73	22,000	.....
ZG42	75S	O	33,000	15,000	17	16	60	22,000	.....
		T6	82,000	72,000	11	11	150	49,000	21,000
Clad ZG42	Alclad 75S	O	32,000	14,000	17	..	...	22,000	.....
		T6	76,000	67,000	11	..	...	46,000	.....

[a] The values given in this table are, in general, weighted averages which have taken into account the small variations introduced by size, shape or method of manufacture. Although, as a result, they may not exactly describe any one specific product, they provide an entirely sound basis for comparing the several alloys and tempers, and selecting the most suitable one which is commercially available in the desired product.

[b] The modulus of elasticity varies somewhat with the alloy and is about 2% higher in compression than in tension. For most calculations, a value of 10,300,000 psi. can be used for all alloys, but the following values, which are averages of the tension and compression moduli, can be used if more exact results are desired: 2S, 3S, 4S, 53S, 61S and 63S, 10,000,000 psi.; 52S, 10,200,000 psi.; 75S, 10,400,000 psi.; 14S and 24S, 10,600,000 psi. The modulus of rigidity is approximately 3,900,000 psi. and Poisson's ratio is about one-third.

[c] The endurance limits are based on 500,000,000 cycles of completely reversed stress using the R. R. Moore type of machine and specimen.

[d] Sheet less than 0.040-in. thick will have slightly lower strengths.

[e] 15 to 20% higher for extrusions more than 3/4-in. thick.

[f] Sheet more than 0.063-in. thick will have slightly higher strengths.

[g] The values given are for sheet. Extrusions will be 8 to 10% higher.

Table 2—Mechanical Properties of Aluminum Sand-Casting Alloys[a]

ASTM No.	Commercial Designation	Temper	Minimum Values for Specifications: Tensile Strength, Psi.	Minimum Values for Specifications: Elongation, % in 2 in.	Typical Values: Tensile Strength, Psi.	Typical Values: Tensile Yield Strength (Offset = 0.2%), Psi.	Typical Values: Elongation, % in 2 In.	Typical Values: Compressive Yield Strength[b] (Offset = 0.2%), Psi.	Typical Values: Brinell Hardness, 500-Kg. Load, 10-Mm. Ball	Typical Values: Shear Strength, Psi.	Typical Values: Endurance Limit, R. R. Moore Type Specimen; 500,000,000 Cycles, Psi.
S1, S2	43	....	17,000	3.0	19,000	9,000	6.0	10,000	40	14,000	6,500
CS5	108	....	19,000	1.5	21,000	14,000	2.5	14,000	55	20,000	8,000
....	112	....	19,000	[c]	24,000	15,000	1.5	17,000	70	20,000	9,000
CS22	113	....	19,000	[c]	24,000	15,000	1.5	17,000	70	20,000	9,000
CG1	122	-T2	23,000	[c]	27,000	20,000	1.0	20,000	80	21,000	9,500
CG1	122	-T61	30,000	[c]	40,000	30,000	[d]	43,000	115	29,000	8,500
CN21	142	-T21	23,000	[c]	27,000	18,000	1.0	18,000	70	21,000	6,500
CN21	142	-T571	29,000	[c]	32,000	28,000	0.5	34,000	85	27,000	8,000
CN21	142	-T77	21,500	[c]	28,000	25,000	2.0	25,000	75	24,000	9,500
C-1	195	-T4[e]	29,000	6.0	32,000	16,000	8.5	16,000	60	24,000	6,000
C-1	195	-T6	32,000	3.0	36,000	24,000	5.0	25,000	75	30,000	6,500
C-1	195	-T62	36,000	[c]	40,000	30,000	2.0	38,000	95	31,000	7,000
....	212	....	19,000	[c]	23,000	14,000	2.0	14,000	65	20,000	8,000
G1	214	....	22,000	6.0	25,000	12,000	9.0	12,000	50	20,000	5,500
GS1	B214	....	17,000	[c]	20,000	13,000	2.0	15,000	50	17,000	.....
....	F214	....	17,000	[c]	20,000	12,000	3.0	12,000	50	.....	.....
G3	220	-T4	42,000	12.0	46,000	25,000	14.0	26,000	75	33,000	7,000
SC9	319	....	23,000	[c]	27,000	18,000	2.0	18,000	70	.....	10,000
SC9	319	-T6	31,000	1.5	36,000	24,000	2.0	24,000	80	.....	10,000
SC-21	355	-T51	25,000	[c]	28,000	23,000	1.5	24,000	65	22,000	7,000
SC-21	355	-T6	32,000	2.0	35,000	25,000	2.5	29,000	80	30,000	8,500
SC-21	355	-T61	36,000	[c]	39,000	35,000	1.0	37,000	90	32,000	.....
SC-21	355	-T7	35,000	[c]	38,000	36,000	0.5	36,000	85	26,000	8,500
SC-21	355	-T71	30,000	[c]	35,000	29,000	1.5	29,000	75	.....	10,000
SG-1	356	-T51	23,000	[c]	25,000	20,000	2.0	22,000	60	18,000	7,500
SG-1	356	-T6	30,000	3.0	33,000	24,000	4.0	24,000	70	27,000	8,000
SG-1	356	-T7	31,000	[c]	34,000	30,000	2.0	30,000	75	18,000	.....
SG-1	356	-T71	25,000	3.0	28,000	21,000	4.5	21,000	60	16,000	.....

[a] Tension and hardness values obtained from standard half-inch diameter tensile test specimens, individually cast in green sand molds, and tested without machining off the surface. The modulus of elasticity varies somewhat with the alloy, but an average value of 10,300,000 psi. can be used for most calculations.

[b] Results of tests on specimens having an *l/r* ratio of 12.

[c] Not specified. The error in determining low elongations is comparable with the value being measured.

[d] Less than 0.5%.

[e] On standing at room temperature for several weeks, the properties will approach those of the T6 condition.

Table 3—Mechanical Properties of Aluminum Permanent-Mold Casting Alloys[a]

			Minimum Values —for Specifications—		Typical Values						
ASTM No.	Commercial Designation	Temper	Tensile Strength, Psi.	Elongation, % in 2 In.	Tensile Strength, Psi.	Tensile Yield Strength (Offset = 0.2%), Psi.	Elongation, % in 2 In.	Compressive Yield Strength[b] (Offset = 0.2%), Psi.	Brinell Hardness, 500-Kg. Load, 10-Mm. Ball	Shear Strength, Psi.	Endurance Limit, R.R. Moore Type Specimen; 500,000,000 Cycles, Psi.
S1, S2	43	...	21,000	5.0	24,000	9,000	9.0	9,000	45	18,000	.....
SC1	A108	..	24,000	[c]	28,000	16,000	2.0	16,000	70	25,000	.....
CS22	113		24,000	[c]	28,000	19,000	2.0	19,000	70	23,000	.....
...	C113	...	25,000	[c]	30,000	24,000	1.0	24,000	80	24,000	9,500
CG-1	122	-T52	33,000	[c]	35,000	31,000	1.0	31,000	100	25,000	.....
CG-1	122	T551	35,000	[c]	37,000	35,000	[d]	40,000	115	27,000	8,500
CG-1	122	T65	40,000	[c]	48,000	36,000	[d]	36,000	140	30,000	9,000
SN41	A132	T551	31,000	[c]	36,000	28,000	0.5	30,000	105	24,000	.....
SN41	A132	T65	40,000	[c]	47,000	43,000	0.5	43,000	125	27,000	.....
...	D132	-T5	31,000	[e]	36,000	28,000	1.0	28,000	100	.....	.....
...	138	...	26,000	[e]	32,000	24,000	1.5	32,000	100	22,000	.....
CN-1	142	-T571	34,000	[e]	40,000	34,000	1.0	34,000	105	26,000	10,500
CN-1	142	-T61	40,000	[e]	47,000	42,000	0.5	46,000	110	31,000	9,500
CS4	B195	-T4[f]	33,000	4.5	37,000	19,000	9.0	22,000	75	30,000	9,500
CS4	B195	-T6	35,000	2.0	40,000	26,000	5.0	26,000	90	32,000	10,000
CS4	B195	-T7	33,000	3.0	39,000	20,000	4.5	20,000	80	.....	.....
GZ-1	A214	...	22,000	2.5	27,000	16,000	7.0	17,000	60	22,000	.....
SC8	319	...	28,000	1.5	34,000	19,000	2.5	19,000	85	24,000	.....
SC8	319	-T6	34,000	2.0	40,000	27,000	3.0	27,000	95	.....	.....
SC21	355	-T51	27,000	[e]	30,000	24,000	2.0	24,000	75	24,000	.....
SC21	355	-T6	37,000	1.5	43,000	27,000	4.0	27,000	90	30,000	9,000
SC21	355	-T62	42,000	[c]	45,000	40,000	1.5	40,000	105	36,000	.....
SC21	355	-T7	36,000	[e]	40,000	30,000	2.0	30,000	85	30,000	.....
SC21	355	-T71	34,000	[e]	36,000	31,000	3.0	31,000	85	26,000	.....
SG1	356	-T6	33,000	3.0	40,000	27,000	5.0	27,000	90	.....	.....
SG1	356	-T7	29,000	4.0	33,000	24,000	5.0	24,000	70	.....	.....
...	750	-T5	18,000	8.0	20,000	8,500	10.0	8,500	45	14,000	9,000

[a] Tension and hardness values obtained from standard half-inch diameter tensile test specimens, individually cast in a permanent mold, and tested without machining off the surface. The modulus of elasticity varies somewhat with the alloy, but an average value of 10,300,000 psi. can be used for most calculations.

[b] Results of tests on specimens having an l/r ratio of 12.

[c] Not specified. The error in determining low elongations is comparable with the value being measured.

[d] Less than 0.5%.

[e] On standing at room temperature for several weeks, properties approach those of the T6 condition.

Table 4—Nominal Composition of Aluminum Alloys[a]

ASTM No.	Commercial Designation	Per Cent of Alloying Elements, Aluminum and Normal Impurities Constitute Remainder					
		Copper	Silicon	Manganese	Magnesium	Zinc	Chromium
				Wrought Alloys			
A2	2S[b]	...	...	...	...	...	...
M1	3S	...	...	1.2	...	...	...
MG1	4S	...	...	1.2	1.0	...	...
CS41	14S	4.4	0.8	0.8	0.4	...	...
CM21	17S	4.0	...	0.5	0.5	...	...
CG21	24S	4.5	...	0.6	1.5	...	...
....	43S	...	5.0	...	...	...	...
GR1	52S	...	...	...	2.5	...	0.25
GS22	53S or R353	...	0.7	...	1.3	...	0.25
GS21	61S or R361	0.25	0.6	...	1.0	...	0.25
GS2	63S	...	0.4	...	0.7	...	...
ZG42	75S	1.6	...	...	2.5	5.6	0.3
				Sand-Casting Alloys			
S1, S2	43	...	5.0	...	...	...	...
CS5	108	4.0	3.0	...	...	...	...
....	112	7.0	...	...	...	...	...
C1	195	4.5	0.8	...	...	1.7	...
SC9	319	3.5	6.3	...	...	...	...
SC21	355	1.3	5.0	...	...	...	...
SG1	356	...	7.0	...	0.5	...	...
					0.3	...	...
				Permanent Mold-Casting Alloys			
S1, S2	43	...	5.0	...	...	...	...
SC1	A108	4.5	5.5	...	...	...	...
....	C113	7.0	3.5	...	...	...	...
CS4	B195	4.5	2.5	...	...	...	...
SC8	319	3.5	6.3	...	...	...	...
SC21	355	1.3	5.0	...	...	...	...
SG1	356	...	7.0	...	0.5	...	...
					0.3	...	...

[a] Heat-treatment symbols have been omitted since composition does not vary for different heat-treatment practices.
[b] 99% minimum aluminum.

Table 5—Typical Physical Properties of Wrought Alloys

ASTM No.	Commercial Designation	Temper	Specific Gravity	Density, Lb./Cu. In.	Approximate Melting Range, °F.	Electrical Conductivity, % of International Annealed Copper Standard	Thermal Conductivity at 25° C., C.G.S. Units[a]
A2	2S	-O	2.71	0.098	1190–1215	59	0.53
A2	2S	-H18	2.71	0.098		57	0.52
M1	3S	-O	2.73	0.099	1190–1210	50	0.46
M1	3S	-H18	2.73	0.099		40	0.37
MG1	4S	-O	2.72	0.098	1165–1205	42	0.39
MG1	4S	-H38	2.72	0.098		42	0.39
CS41	14S	-O	2.80	0.101	950–1180	50	0.46
CS41	14S	-T6	2.80	0.101		40	0.37
CM21	17S	-O	2.79	0.101	955–1185	45	0.41
CM21	17S	-T4	2.79	0.101		30	0.29
CG21	24S	-O	2.77	0.100	935–1180	50	0.45
CG21	24S	-T3	2.77	0.100		30	0.29
GR1	52S	-O	2.68	0.097	1100–1200	35	0.33
GR1	52S	-H38	2.68	0.097		35	0.33
GS22	53S & R353	-O	2.69	0.097	1075–1205	45	0.41
GS22	53S & R353	-T4 or -T6	2.69	0.097		40	0.37
GS21	61S & R361	-O	2.70	0.098	1080–1205	45	0.41
GS21	61S & R361	-T4 or -T6	2.70	0.098		40	0.37
GS2	63S	-F	2.70	0.098	1140–1205	50	0.46
GS2	63S	-T5 or -T6	2.70	0.098		55	0.50
ZG42	75S	-O	2.80	0.101	890–1180	...	...
ZG42	75S	-T6	2.80	0.101		30	0.29

[a] C.G.S. units = calories per second per square centimeter per centimeter of thickness per degree Centigrade

Table 6—Typical Physical Properties of Casting Alloys

ASTM No.	Commercial Designation	Temper	Specific Gravity	Density, Lb./Cu In.	Approximate Solidification Range, °F.	Electrical Conductivity, % of International Annealed Copper Standard	Thermal Conductivity at 25° C., C.G.S. Units[a]
S1, S2	43		2.64	0.095	1155–1055	37	0.35
S1, S2	43	Annealed[b]	2.64	0.095	1155–1055	42	0.39
CS5	108		2.73	0.099	1170–960	31	0.29
CS5	108	Annealed[b]	2.73	0.099	1170–960	38	0.35
SC1	A108[c]		2.77	0.100	1140–960	37	0.34
	112		2.85	0.103	1150–950	30	0.29
	112	Annealed[b]	2.84	0.103	1150–950	38	0.35
C1	195	-T4	2.75	0.100	1190–960	35	0.33
C1	195	-T62	2.75	0.100	1190–960	37	0.35
CS4	B195	-T4[c]	2.78	0.101	1180–965	35	0.33
CS4	B195	-T6[c]	2.78	0.101	1180–965	50	0.45
CS4	B195	-T62	2.78	0.101	1180–965	...	...
SC9	319		2.74	0.099	1120–950	27	0.27
SC9	319[c]		2.77	0.100	1120–950	29	0.28
SC21	355	-T51	2.66	0.096	1160–1000	43	0.40
SC21	355	-T6	2.66	0.096	1160–1000	36	0.34
SC21	355	-T61	2.66	0.096	1160–1000	37	0.35
SC21	355	-T7	2.66	0.096	1160–1000	42	0.39
SC21	355	-T6[c]	2.69	0.097	1160–1000	39	0.36
SG1	356	-T51	2.62	0.095	1145–1055	43	0.40
SG1	356	-T6	2.63	0.095	1145–1055	39	0.36
SG1	356	-T7	2.62	0.095	1145–1055	40	0.37
SG1	356	-T6[c]	2.66	0.096	1145–1055	41	0.38

[a] C.G.S. units = calories per second per square centimeter per centimeter of thickness per degree Centigrade.

[b] While castings are not commonly annealed, similar effects on conductivities may result from the slower rate of cooling of thick sections as compared with thin ones and other variables in foundry practices. Comparison of the values for as-cast and annealed specimens will show the extent to which variations may be expected, depending upon differences in thermal conditions in the production of different types of castings.

[c] Chill cast samples; all other samples cast in green sand molds.

Table 7—Approximate Tip Sizes and Gas Pressures for Gas Welding

Metal Thickness, B. & S. Gage	Oxy-Hydrogen			Oxy-Acetylene		
	Diameter of Orifice in Tip, In.	Oxygen Pressure, Psi.	Hydrogen Pressure, Psi.	Diameter of Orifice in Tip, In.	Oxygen Pressure, Psi.	Acetylene Pressure, Psi.
24–22	0.035	1	1	0.025	1	1
20–18	0.045	1	1	0.035	1	1
16–14	0.065	2	1	0.045	2	2
12–10	0.075	2	1	0.055	3	3
1/8–3/16	0.095	3	2	0.065	4	4
1/4	0.105	4	2	0.075	5	5
5/16	0.115	4	2	0.085	5	5
3/8	0.125	5	3	0.095	6	6
5/8	0.150	8	6	0.105	7	7

Table 8—Data for Gas Welding Tank-Type Structures

Gage, In.	Gas Used	Diameter Opening Tip, In.	Wire Diameter, In.	Lb. Wire/ 100 Ft. of Weld	Lb. Flux/ 100 Ft. of Weld	Rate of Welding, Ft./Hr.
1/16	Oxy-hydrogen	0.055	0.125	6.0	2.0	12.0
1/8	Oxy-hydrogen	0.075	0.146	12.5	3.0	10.0
1/4	Oxy-acetylene	0.075	0.184	20.0	5.5	8.0
3/8	Oxy-acetylene	0.084	0.184	30.0	10.0	6.0
1/2	Oxy-acetylene	0.095	0.250	35.0	15.0	3.5
5/8	Oxy-acetylene	0.095	0.312	40.0	18.0	3.5

Table 9—Electrode Sizes and Machine Settings for Manual Shielded Metal-Arc and Carbon-Arc Welding

Metal Thickness, In.	Electrode Diameter, In.	Approximate Current, Amp.	No. of passes		Electrode Consumption —Lb./100 Ft. of weld—			No. of Electrodes per Lb.
			Butt Joints	Lap and Tee Joints	Butt	Lap	Tee	
0.081	1/8	60	1	1	4 7	5.3	6.3	32
0.101	1/8	70	1	1	5.0	5.7	6.3	32
0.125	1/8	80	1	1	5.7	6.25	6.3	32
0.156	1/8	100	1	1	6.3	6.5	6.5	32
0.187	5/32	125	1	1	8.7	9.0	9.0	23
0.250	3/16	160	1	1	12.0	12.0	12.0	17
0.375	3/16 for Laps and Fillets 1/4 for Butts	200	2	3	25	29	35	17
0.500	3/16 for Laps and Fillets 1/4 for Butts	300	3	3	35	35	35	17

Table 10—Machine Settings for Inert-Gas Metal-Arc Welding

Metal Thickness, In.	No. Passes	Current, Amp.	Electrode Diameter, In.	Argon Volume, Cu. Ft./ Hr.[a]	Cup Opening Diameter, 1/16 in.	Welding Rod Diameter, In.
0.051	1	70	1/16	12	6 7	1/8
0.064	1	80	3/32	14	7	1/8
0.081	1	90	3/32	14	7	5/32
0.101	1	120	1/8	15	7–8	5/32
0.125	1	140	1/8	15	7–8	5/32
0.187	1	160	1/8	15	7–8	3/16
0.250	2	220	5/16	20	8	3/16
0.375	2	300	1/4	24	8–10	1/4
0.500	3	500	1/4	24	10	1/4
1.000[b]	10–14	500	5/16	30	10–12	5/16
2.000[b]	20–30	600	5/16	30	10–12	5/16

[a] Multiply reading on oxygen flowmeter by 1.5 to convert from liters per minute to cubic feet per hour of argon gas.
[b] Preheat to 400° F.

Table 11—Machine Settings for Automatic Carbon-Arc Welding

Metal Thickness, In.	Current, Amp.	Arc Voltage	Rod Size, In.	Wire Speed, In./Min	Rod Consumption, Lb./100 Ft. of Weld	Flux Consumption, Lb./100 Ft. of Weld	Welding Speed, In./Min.
0.188	310	35	5/32	16.8	2.5	17	16
0.250	360	36	5/32	20.3	3.68	21	14
0.312	380	38	1/4	9.6	4.78	26	12.3
0.375	390	38	1/4	10.2	5.0	28	12
0.500	410	39	1/4	9.3	7.8	51	7.1

Table 12—Machine Settings for Atomic Hydrogen Welding

Metal Thickness, In.	Current, Amp.	Hydrogen Consumption, Cu. Ft./Hr.	Welding Rod Diameter, In.
0.064	10	30	1/8
0.081	15	30	5/32
0.101	21	40	5/32
0.125	27	40	3/16
0.187	33	45	3/16
0.250	39	45	3/16
0.375	45	45	1/4

Table 13—Brazing Filler Metal

Nominal Composition	Melting Range, ° F.
Al-5% Si	1070–1165
Al-7.5% Si	1070–1135
Al-10% Si	1070–1100
Al-12% Si	1070–1080
Al-10% Si-4% Cu	970–1085

Table 14—Machine Settings for A.C. Spot Welding

Thickness, In.	Time, Cycles (60 per Sec.)	Current, Amp.	Electrode Force, Lb. Min.	Max.
0.016	4	14,000	200	400
0.020	6	16,000	300	500
0.025	6	17,000	300	500
0.032	8	18,000	400	600
0.040	8	20,000	400	600
0.051	10	22,000	500	700
0.064	10	24,000	500	700
0.081	12	28,000	600	800
0.102	12	32,000	800	1000
0.128	15	35,000	800	1200

Table 15—Machine Settings for Spot Welding Alclad or Pureclad 24S-T with Electromagnetic and Condenser-Discharge Equipment

Sheet Thickness, In.	Electrode Tip Contour	Electrode Force, Lb. Weld	Forge	Welding Current, Amp.	Shear Strength, Lb.	Transformer Turns Ratio[a]
0.020	3-in. R. Dome	350	900	23,600	210	300
0.025	3-in. R. Dome	390	975	25,500	300	300
0.032	3-in. R. Dome	440	1100	28,000	430	300
0.040	3-in. R. Dome	500	1250	31,000	580	300
0.051	4-in. R. Dome	620	1550	36,500	820	300
0.064	4-in. R. Dome	700	1750	41,000	1060	300
0.072	4-in. R. Dome	770	1925	44,200	1210	450
0.081	4-in. R. Dome	840	2100	47,600	1380	450
0.091	4-in. R. Dome	900	2250	51,000	1570	450
0.102	6-in. R. Dome	1050	2600	57,900	1850	450
0.125	6-in. R. Dome	1250	3100	66,800	2180	450

[a] For condenser-discharge machines.

Table 16—Suggested Spot-Weld Electrode Tip Radius

Temper	Thickness of Parts, In. Up to 0.020	0.021–0.032	0.033–0.064	0.065–0.094	0.095–0.125
Annealed and as-extruded	2	3	4	4	..
Intermediate tempers of nonheat-treated alloys	2	3	3	4	4
Heat treated	1	2	3	4	4

NOTE: If flat surface on one side is required, one electrode face is made to above radius and other is flat.

Table 17—Minimum Shear Strength for Spot Welds

Nominal Thickness of Thinner Sheet, In.	Aluminum and Aluminum Alloys, Bare and Clad: Ultimate Strength, 56,000 Psi. and Above (Min.), Lb.	Ultimate Strength, 28,000 Psi. to 56,000 Psi. (Min.), Lb.	Ultimate Strength, 19,500 Psi. to 28,000 Psi (Min.), Lb.	Ultimate Strength, Below 19,500 Psi. (Min.), Lb.
0.010	60	50	..	..
0.016	108	98	70	50
0.025	185	175	145	110
0.032	260	235	210	165
0.040	345	310	300	225
0.051	480	442	410	300
0.064	690	625	565	400
0.072	845	735	655	455
0.081	1050	865	775	530
0.094	1345	1065	900	627
0.102	1535	1200	950	685
0.114	1830	1360	1005	740
0.125	2120	1625	1050	785
0.140	2525	....	....	...
0.156	2995	....	....	...
0.189	4000	....	....	...

Table 18—Machine Settings for Producing Continuous, Gas-Tight Seam Welds[d]

Thickness of One Sheet, In.	Spots per In.	*On* Plus *Off* Time,[a] Cycles	Electrode Travel Speed,[b] Ft./Min.	*On* Time,[c] Cycles Min.	Max.	Welding Pressure,[d] Lb.	Welding Current,[d] Amp.	Width of Weld, In.
0.010	25	3 1/2	3.4	1/2	1	420	19,500	0.08
0.016	21	3 1/2	4.1	1/2	1	500	22,000	0.09
0.020	20	4 1/2	3.3	1/2	1 1/2	540	24,000	0.10
0.025	18	5 1/2	3.0	1	1 1/2	600	26,000	0.11
0.032	16	5 1/2	3.4	1	1 1/2	690	29,000	0.13
0.040	14	7 1/2	2.9	1 1/2	2 1/2	760	32,000	0.14
0.051	12	9 1/2	2.6	1 1/2	3	860	36,000	0.16
0.064	10	11 1/2	2.6	2	3 1/2	960	38,500	0.19
0.081	9	15 1/2	2.1	3	5	1090	41,000	0.22
0.102	8	20 1/2	1.8	4	6 1/2	1230	43,000	0.26
0.128	7	28 1/2	1.5	5 1/2	9 1/2	1350	45,000	0.32

[a] Use next higher full cycle setting if timer is not equipped to give antipole starting of current.
[b] Should be adjusted to give desired spots per inch.
[c] *On* time must be set at full cycle setting if *On* plus *Off* time is set at full cycle setting.
[d] Welding pressure and welding current are adjusted to give desired width of weld. Values are for 52S-H14 aluminum alloy. Use lower pressures for 52S-O or 3S-H14 aluminum alloys.

BIBLIOGRAPHY

1. *Brazing the Aluminum Alloys,* G. O. Hoglund, The Welding Journal Res. Suppl., April 1940.

2. *The Flow of Metal in Brazing Aluminum,* M. A. Miller, The Welding Journal Res. Suppl., October 1941.

3. *Summary of Results of Tests Made by Aluminum Research Laboratories of Spot Welded Joints and Structural Elements,* E. C. Hartmann and G. W. Stickley, NACA TN 869, November 1942.

4. *Aluminum Brazing Sheet—Fundamentals of Metal Flow,* M. A. Miller, The Welding Journal Res. Suppl., December 1943.

5. *Correlation of the Strength and Structure of Spot Welds in Aluminum Alloys,* F. Keller and D. W. Smith, The Welding Journal Res. Suppl., January 1944.

6. *Tentative Specifications for Aluminum and Aluminum Alloy Metal Arc Welding Electrodes,* A5.3–43T, American Welding Society, The Welding Journal, March 1944. (Also available in bulletin form.)

7. *A Paper on Multi-Arc Welding of Aluminum Alloys,* M. R. Rivenburgh and C. W. Steward, The Welding Journal Res. Suppl., July 1944.

8. *The Surface Treatment of Alclad 24S-T Prior to Spot Welding,* W. F. Hess, R. A. Wyant and B. L. Averbach, The Welding Journal Res. Suppl., August 1944.

9. *Magnetic Oscillograph Equipment for Development of Aluminum Alloy Spot Welding and Production Control of Welding Machines,* G. W. Scott and A. A. Burr, The Welding Journal Res. Suppl., August 1944.

10. *Joining Aluminum Alloys,* E. C. Hartmann, G. O. Hoglund and M. A. Miller, Steel, August 7, 14, 21, 28, 1944 and September 4, 11, 1944.

11. *The Surface Treatment at Room Temperature of Aluminum Alloys for Spot Welding,* W. F. Hess, R. A. Wyant and B. L. Averbach, The Welding Journal Res. Suppl., September 1944.

12. *Characteristics of Welding Arcs on Aluminum in Atmospheres of Helium and Argon,* F. A. Wassell, The Welding Journal Res. Suppl., October 1944.

13. *Radiography for Development and Control of Aluminum Alloy Spot Welding,* G. W. Scott, L. G. Sutton and J. H. Widmyer, The Welding Journal Res. Suppl., November 1944.

14. *Automatic Carbon Arc Welding,* W. J. Conley, Welding Engineer, February 1945.

15. *Summary of Observations of Cracking in Spot Welds in Alclad 24S-T,* R. A. Wyant, The Welding Journal Res. Suppl., March 1945.

16. *Progress in Heliarc Welding,* T. E. Piper, Automotive and Aviation Industries, August 15, 1945.

17. *Measuring Surface Resistance of Aluminum Alloys,* The Welding Journal Res. Suppl., September 1945.

18. *Railroad Tank Cars of All-Welded Aluminum,* R. E. Haas, The Welding Journal, October 1945.

19. *Instrumentation of the Spot Welder and Investigation of the Spot Welding of 0.091-In. 24S-T Alclad Sheet,* R. C. McMaster and N. A. Begovich, The Welding Journal Res. Suppl., October 1945.

20. *The Aluminum Dip Brazing Process,* C. L. Benson and R. N. Weber, Aluminum and Magnesium, December 1945.

21. *The Spot Welding of Dissimilar Thicknesses of Alclad 24S-T,* W. F. Hess, R. A. Wyant and B. L. Averbach, The Welding Journal Res. Suppl., December 1945.

22. *An Investigation of Current Wave-Form for Spot Welding Alclad 24S-T 0.20 In. Thickness,* W. F. Hess, R. A. Wyant and B. L. Averbach, The Welding Journal Res. Suppl., January 1946.

23. *The Flash Welding of Alclad 24S-T Alloy in the 0.064 In. Thickness,* W. F. Hess and F. J. Winsor, The Welding Journal Res. Suppl., January 1946.

24. *Metal Flow and Fillet Formation in Brazing Aluminum,* M. A. Miller, The Welding Journal Res. Suppl., February 1946.

25. *Method for Welding Sheet Aluminum to SAE 4140 Steel,* W. F. Hess and E. F. Nippes, Jr., The Welding Journal Res. Suppl., March 1946.

26. *An Investigation of Electrode Pressure Cycles and Current Wave Forms for Spot Welding Alclad 24S-T,* W. F. Hess, R. A. Wyant, B. L. Averbach and F. J. Winsor, The Welding Journal Res. Suppl., March 1946.

27. *Electric Resistance Brazing of Structural Aluminum Alloys,* W. F. Hess and E. F. Nippes, Jr., The Welding Journal Res. Suppl., April 1946.

28. *An Investigation of the Effect of Spot Welding on the Sheet Efficiency of Aluminum Alloy 24S-T,* W. F. Hess, R. A. Wyant and F. J. Winsor, The Welding Journal Res. Suppl., May 1946.

29. *Further Investigation of the Effect of Spot Welds on the Sheet Efficiency of Alclad 24S-T,* W. F. Hess, R. A. Wyant and F. J. Winsor, The Welding Journal Res. Suppl., July 1946.

30. *Pressure Welding Thin Aluminum Parts,* H. E. Linsley, Iron Age, August 8, 1946.

31. *Interpretation of Radiographs of Spot Welds in 24S-T and 75S-T Aluminum Alloys,* R. C. McMaster and F. C. Lindvall, The Welding Journal, August 1946.

32. *Development of a Two-Row High Strength Spot Welded Lap Joint in 24S-T Alclad Aluminum Alloy,* L. M. Crawford and J. E. Pease, The Welding Journal, December 1946.

33. *Radiography of Spot Welds in Various Sheet Gages and Dissimilar Gage Combinations,* R. C. McMaster, F. C. Lindvall and L. P. Gaard, The Welding Journal, January 1947.

34. *Static and Fatigue Tests of Arc Welded Aluminum Alloy 61S-T Plate,* E. C. Hartmann, M. Holt and A. N. Zomboky, The Welding Journal Res. Suppl., March 1947.

35. *Radiography and the Fatigue Strength of Spot Welds in Aluminum Alloys,* R. C. McMaster and H. J. Grover, The Welding Journal, March 1947.

36. *Static Strength Tests of Fillet Welds on Aluminum Alloy 61S-T Plate,* R. L. Moore, The Welding Journal Res. Suppl., October 1947.

37. *Static and Fatigue Strengths of Welded Joints in Aluminum-Manganese Alloy Sheet and Plates,* R. L. Templin and M. Holt, The Welding Journal Res. Suppl., December 1947.

38. *Petroleum Pipe Lines, Inert Gas Welded Aluminum Pipe Line to Carry "Sour" Oil,* Petroleum Engineer, July 1948.

39. *Pressure Cold Welding Aluminum,* Light Metals, July 1948; see also Iron Age, August 19, 1948.

40. *Aluminum Field-Erected Storage Tanks,* F. L. Plummer, The Welding Journal, October 1948.

41. *Welds, Testing Strength of Welded Joints in Thick Aluminum Plates,* C. B. Voldrich, American Society of Mechanical Engineers, October 1948.

42. *The Gas Shielded Metal Arc-Welding Process,* Jesse S. Sohn and A. N. Kugler, The Welding Journal, November 1948.

CHAPTER 33

MAGNESIUM AND MAGNESIUM ALLOYS*

GENERAL PROPERTIES

MAGNESIUM AND all of the commercial magnesium alloys produced in the form of sheet, plate, extrusions and sand or permanent mold castings are weldable. The commercial welding processes most widely used are inert-gas metal-arc welding, gas welding and spot welding. Other processes used include brazing and soldering, and to a lesser extent seam, flash and pressure welding. All of these processes are discussed in this chapter, along with the common applications and limitations of each. In addition, certain secondary considerations such as cleaning, chemical treatments, inspection and testing, and stress relieving are covered.

In order to effectively weld magnesium and design welded structures for magnesium alloys, an understanding of the general properties of the metal itself is necessary. The following section covers the basic physical, chemical and metallurgical characteristics of magnesium and the compositions and properties of its commercially used alloys. Also discussed are the effect of alloy composition on the weldability and other metallurgical factors concerned with weld properties obtained.

Basic Characteristics

Magnesium is well known for its extreme lightness, excellent machinability and weldability as well as the high strength-to-weight ratio of its alloys. It has a specific gravity of 1.74 and weighs 109 lb. per cu. ft. or approximately 1 oz. per cubic inch. It is roughly one-fifth the weight of steel and two-thirds the weight of aluminum. Pure magnesium melts at 1204°F. and boils at 2007°F. Its degree of contraction from a liquid to a solid at its melting point is about 4.3% and from a liquid at its melting point to a solid at room temperature, about 9.7%. The average coefficient of thermal expansion for magnesium alloys in the range form 65 to 750°F. is about 0.000016 in. per in. per °F. The total heat of fusion is approximately 31,000 joules per cubic inch.

From the standpoint of welding, one important characteristic of magnesium is its rapid oxidation when heated to its melting point in air. For this reason, the arc or gas welding of magnesium requires the use of a protective shield such as an inert gas when arc welding or a flux when gas welding. The oxide formed on magnesium surfaces recrystallizes at high temperatures and becomes flaky so that the film tends to break up more readily during welding than the similarly formed oxide on aluminum. Magnesium oxide (MgO) is highly refractory and insoluble in both liquid and solid magnesium. In inert-gas arc welding, magnesium nitride (Mg_3N_2) is sometimes formed as an orange-colored deposit on the tungsten electrode. The nitride is relatively unstable and readily decomposes in the presence of moisture. None of the fumes given off in the welding of magnesium are known to be either harmful or toxic.

Because of its comparatively low melting point, latent heat of fusion and specific heat per unit volume, the amount of heat required to melt magnesium is relatively small. On an equal volume basis, the total heat for fusion is approximately two-thirds that for aluminum and one-fifth that for steel. The high coefficients of thermal expansion and conductivity tend to cause considerable distortion when welding magnesium unless proper precautions are taken. In this respect, magnesium is more critical than steel and behaves more nearly like aluminum.

Magnesium and its alloys have a hexag-

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onal close-packed crystal structure and the amount of deformation which can be performed at room temperature is rather limited. The allowable deformation, however, improves rapidly with increase in temperature so that at temperatures from 400 to 600°F. the metal can be more severely worked than other structural metals at room temperature. Because of this, forming operations such as drawing, bending and spinning, as well as weld peening and straightening are generally done hot.

The probability of fire when welding magnesium alloys is very remote. No serious fires have ever been reported as having been caused by welding. Magnesium alloys will not ignite until their temperature of incipient fusion is reached, and then sustained burning will occur only if this temperature can be maintained in the metal. Magnesium fires usually result from the ignition of finely divided particles such as grinding dust, mill shavings, borings or routing chips. Dry sand, cast-iron chips, dry powdered soapstone or, preferably, one of the graphite-type extinguishers specifically recommended for magnesium fires, should be strategically located throughout any area where machining and welding operations are conducted. Fine particles should be collected in suitable oil baths and stored in closed steel containers.

The corrosion resistance of present-day magnesium alloys is better than that of ordinary iron and on a par with some of the aluminum alloys in normal atmospheres. A gray oxide film forms on the surfaces but this is usually the extent of attack. For maximum corrosion resistance, chemical surface treatments and paint finishes are used. Plating may also be used. Galvanic type of corrosion can be serious when magnesium is in direct contact with other metals in a corrosive atmosphere or electrolyte. It can be avoided by proper selection of metals in contact with the magnesium, or by insulation between the dissimilar metals. Another type of corrosive attack to which some of the higher-alloy-content magnesium alloys are susceptible is stress corrosion. As encountered in other metals, stress corrosion may result in cracking around welds over a period of time if the residual stresses remaining after welding are not removed or decreased below a certain critical value by adequate stress relieving.

Table 1—Commercial Magnesium Alloys

Specifications and Designations				Nominal Compositions, % (Mg = Remainder)			Typical Mechanical Properties — Ultimate Tensile Strength, psi.	Tensile Yield Strength, psi.	Compressive Yield Strength, psi.	Elongation, % in 2 In.
ASTM[a]	Army-Navy	Dow	AMC[b]	Al	Zn	Mn				
Sheet and Plate										
M1 (A)	AN-M-30	Ma	AM3S-O	...	...	1.5	33,000	17,000	15,000	17
M1 (H)	AN-M-30	Mh	AM3S-H	...	...	1.5	37,000	29,000	20,000	8
AZ31X(A)	AN-M-29	FS-1a	AM-C52S-O	3.0	1.0	0.3	37,000	22,000	16,000	21
AZ31X(H)	AN-M-29	FS-1h	AM-C52S-H	3.0	1.0	0.3	43,000	33,000	26,000	11
Extruded Shapes and Structural Sections										
M1	AN-M-26	M	AM3S	...	...	1.5	36,000	25,000	11,000	9
AZ31X	AN-M-27	FS-1	AM-C52S	3.0	1.0	0.3	38,000	29,000	20,000	14
AZ61X	AN-M-24	J-1	AM-C57S	6.5	1.0	0.2	44,000	31,000	20,000	16
AZ80X	AN-M-25	O-1	AM-C58S	8.5	0.5	0.2	46,000	32,000	22,000	14
Sand Castings										
AZ63[c]	AN-M 36	H HTA	AM265-T6	6.0	3.0	0.2	40,000	19,000	19,000	5
AZ92[c]	AN-M-36	C HTA	AM260-T6	9.0	2.0	0.1	40,000	23,000	23,000	2

[a] ASTM designations are based on letter and numeral combinations denoting the major alloying elements and nominal percentages of these elements present. The suffix *X* denotes alloys of the controlled high purity type, (A) annealed and (H) hard rolled.
[b] American Magnesium Corp.
[c] Heat treated and aged.

Magnesium Alloys*

Commercial magnesium is usually alloyed with various amounts of aluminum, manganese and zinc to obtain maximum strength and corrosion resistance. The most commonly used magnesium alloys

* ASTM designations for magnesium alloys used for reference throughout chapter.

and their designations, compositions and mechanical properties are given in Table 1. Table 2 gives the physical properties of these alloys and can be used to compare their welding behaviors.

The two alloys, *AZ31X* and *M1*, in the form of sheet, plate and extrusions, are most widely used for applications involving welding. *AZ31X* alloy has good strength, ductility, toughness and formability and is generally used for high-strength arc-welded structures. *M1* alloy is used more for applications involving gas and arc welding where stress relieving after welding is not practical or necessary. Neither of these alloys can be heat treated to improve its properties, but they are available in the hard-rolled condition if higher strength properties are desired. *AZ61X* and *AZ80X* alloy extrusions or forgings can be welded satisfactorily but are used less frequently than *M1* and *AZ31X*. The *AZ92* and *AZ63* alloys are used almost exclusively in the production of sand and permanent mold castings. Because of their higher alloy contents these alloys are more sensitive to weld cracking than the wrought alloys and are usually preheated before welding. *M1* alloy castings are used for aircraft oil and fuel tank fittings and are generally gas welded to *M1* alloy sheet.

Magnesium alloys using tin, zirconium, cerium and beryllium as alloying elements are being produced. A tin-aluminum alloy, *TA54*, is used for forging and can be satisfactorily welded. Zinc-zirconium alloys, such as *ZK60*, are used for applications requiring the highest strength properties. They have limited weldability, however, due to their high zinc content. Cerium-manganese alloys, containing 5 to 6% cerium and 2% manganese, are used for high temperature applications and can be easily welded. Small additions of beryllium to magnesium alloys are known to make them less susceptible to burning. Beryllium additions have been made to magnesium alloy welding rods but they are not considered especially beneficial as far as arc and gas welding are concerned. In furnace brazing, however, beryllium is added to the brazing alloy to assure freedom from possible ignition in the furnace because of the high temperatures employed.

Metallurgy of Welds

The strength of arc and gas welds in all magnesium alloys except *M1* is fairly high due to their fine grain size which averages around 0.001 in. as compared to 0.003 to 0.015 in. in castings and about 0.0005 in. in sheet. Spot welds have slightly finer grain size than arc or gas welds. Welded joints usually fail in the heat-affected zone adjacent to the weld rather than in the weld metal. This is due to a slight grain growth in the parent metal caused by the welding thermal cycle and, in some cases, an annealing or an overaging effect outside the weld zone. In the high aluminum-zinc casting alloys, another welding effect exists in that incipient fusion of the eutectic may result in small voids in the area around the weld.

Weld metal usually consists of a homogeneous mixture of deposited metal and parent metal with little loss in alloying elements due to either vaporization or diffusion. A list of commercial magnesium welding rod alloys and their common uses is given in Table 3. The use of a filler metal with a lower melting point and greater freezing range than the base metal is often advantageous from the standpoint of operating characteristics, or whenever cracking is probable. It is also possible to obtain slightly higher weld strengths with higher alloy content filler metal.

Table 2—Physical Properties of Magnesium Alloys

Alloy	Approximate Solidification Range, °F.	Thermal Conductivity (C.G.S. Units), 212°F.	Specific Heat Per Unit Volume, 68-212°F.	Approximate Thermal Diffusivity per Unit Volume	Electrical Resistivity, Microhm-centimeters, 68°F.	Density, lb./cu. in.
M1	1200-1185	0.30	0.44	0.68	5.7	0.064
AZ31X	1170- 970	0.23	0.44	0.52	10.0	0.064
AZ61X	1135- 950	0.19	0.45	0.42	12.5	0.065
AZ63	1130- 685	0.18	0.46	0.39	13.0	0.066
AZ80X	1115- 890	0.18	0.45	0.38	14.5	0.065
AZ92	1110- 770	0.16	0.45	0.36	17.0	0.066

current has been introduced. With a.c., single-pass butt welds can be made in magnesium plate over 1-in. thick without requiring any beveling or root opening. For welding thin sheet material both a.c. and d.c. equipment are satisfactory. Direct current may be more suitable in some cases when welding without a backing. In general, welds made with direct current have a smoother surface appearance than welds made with alternating current.

Direct current welding machines should be equipped with a continuous amperage control in the low ranges to obtain the fine current adjustments needed. Only reverse polarity, electrode positive, is practical since straight polarity is difficult to handle. It is desirable that a.c. machines be equipped with a primary contactor which can be operated by a control switch on the torch or by a foot switch for starting and stopping the arc. Otherwise, arcing while approaching or drawing the electrode away from the work may result in *burned spots* on the surfaces.

Shielding Gas.—Both helium and argon can be used as the shielding gas for a.c. or d.c. welding. With d.c., helium is generally preferred because of the better arc stability obtained. When using argon, a much closer arc length must be held due to its lower ionization potential and loss of cathode spot with arc lengths greater than $^1/_{16}$ inch. With direct current and helium, the electron current is carried by the magnesium ions present. The same is true with argon at arc voltages below the first ionization potential of argon, i.e., about 16 volts. Further discussion of arc characteristics is given in Chapter 12.

With a.c., argon is most frequently used because of its greater density. There seems to be no appreciable difference in arc characteristics with these gases when welding with alternating current. The argon or helium used must be of very high purity. Presence of small amounts of moisture, hydrogen or hydrocarbons will result in porous welds. Nitrogen is not known to be critical in amounts below 1% but about 7%, will decrease the welding speed by about one-half.

Base-Metal Preparation.—The bright-chrome-pickle is recommended for chemical cleaning of production parts to be arc welded. Mechanical cleaning can be done satisfactorily with steel wool, abrasive cloth or power wire brush. Edges to be welded should be smooth and free from loose pieces or pits which might contain any contamination such as oil or oxidation products. Milled, sawed, routed, sanded or filed edges are satisfactory. Sheared edges are satisfactory for thin-gage sheet stock up to about 0.080 inch. Thicker gages should be double-sheared, which consists of cutting a thin strip to final dimensions on the second shear cut. The welding rod to be used should be cleaned with steel wool, or by a bright-chrome-pickle treatment in the case of coiled rod.

Typical joint preparations used for welding various gages of magnesium sheet and plate by inert-gas metal-arc welding are shown in Fig. 1. In general, less preparation is required for welding with a.c. than for welding with d.c. because of the greater penetration obtained. A slight bevel or chamfer is sometimes used on the bottom edges of square butt joints to avoid a thin dark oxide line on the weld bead. Flanged edges are not normally used because of the inability to make sharp bends on magnesium sheet without the use of heat. Double-beveled joints are usually more desirable than single-beveled joints from the standpoint of distortion.

Abutting edges should fit as tightly as possible. A tapered opening of about $^1/_8$ in. per foot of seam length can be employed on long straight seams to minimize distortion if jigging is not to be used. Tack welds should range in size and spacing from $^1/_{16}$-in. tacks 1 or 2 in. on centers in 0.064-in. sheet to about $^1/_4$-in. tacks 4 or 5 in. on centers in $^1/_4$-in. plate. To prevent the seam pulling apart, tack welds should start a short distance from the end of the seam. Straightening during and after tacking can be accomplished by hammering with a soft leather or wood mallet. Tack welds used for welding reinforcement sections onto flat panels usually give less distortion when tacks are placed opposite rather than staggered.

Welding jigs are necessary for most production work especially for thin sheet material. Due to the high coefficients of thermal conductivity and expansion of magnesium alloys, these jigs must be very rigid to resist any movement of parts during welding. Hold-down bars

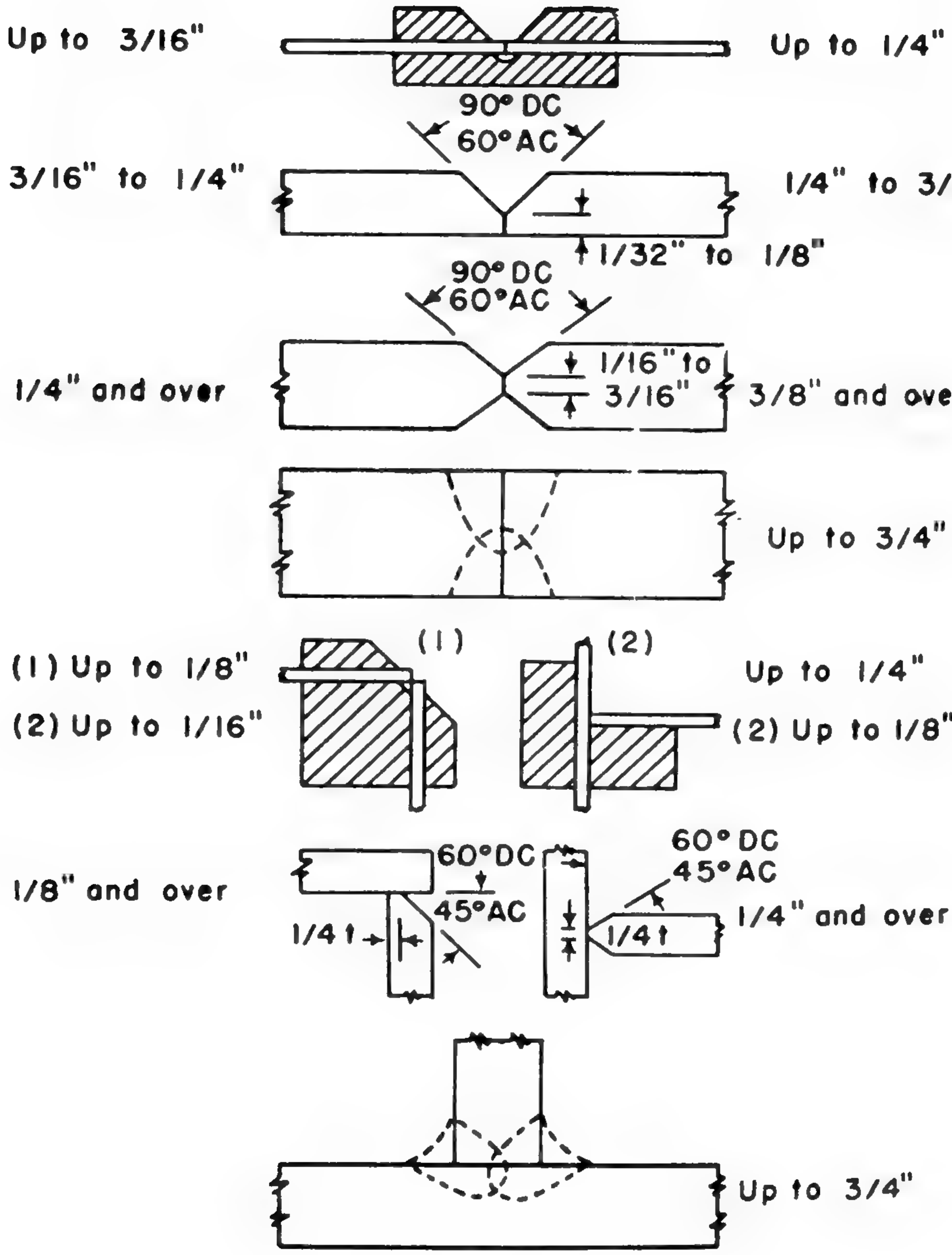

Fig. 1.—Joint Preparation for Inert-Gas Metal-Arc Welding

must exert enough pressure to prevent the edges from lifting over each other or raising away from the backing plate. Backing plates (see Table 5) can be made from magnesium, steel or aluminum. The size of groove required in the backing plate depends upon the thickness of the material welded. It is important that the backing plate be free from all traces of oil or rust to avoid porosity. Cleaning with carbon tetrachloride or other suitable solvents before welding may be necessary.

Table 5—Backing Plate Groove Dimensions for Inert-Gas Metal-Arc Welding

Material Thickness, In.	Depth × Width, In.
Up to 0.064	1/32 × 1/8
0.064–0.102	1/16 × 3/16
0.102–0.188	3/32 × 1/4
0.188–0.250	1/8 × 5/16
1/4	1/8 × 3/8
3/8	5/32 × 1/2
1/2	5/32 × 3/4

Welding Technique.—Data pertaining to current settings, inert-gas flow, tungsten electrode size and welding rod size for d.c. and a.c. welding of various gages of magnesium alloy sheet and plate are given in Table 6. The amount of gas flow required varies with the type and size of weld being made. Approximately twice as much helium as argon is necessary to afford the same protection. Ideally, the gas should start flowing a fraction of a second before the arc is struck and continue for a few seconds after the arc is stopped to protect the weld metal and electrode while cooling.

Details of the operation of the welding torch are covered in Chapter 12. Briefly, the d.c. arc is established by brushing the electrode over the surface. The average arc length should be about 1/8 in. when using helium and about 1/16 in. when using argon. With a.c., it is desirable to start and stop the arc by means of a remote control switch. When welding with a.c., the end of the electrode can be held almost flush with or slightly below the surface of the work to get maximum penetration. Accidental touching of the surface with the electrode will not tend to cause it to stick to the magnesium as in welding other metals. The torch should be held with the electrode nearly perpendicular to the work, and the welding rod added from a position as nearly parallel with the weld surface as practical.

Welding should progress in a straight line along the weld seam at a uniform rate of speed so that an even bead is deposited. A weaving or rotary motion is not recommended except for large corner joints or fillet welds. A back-and-forth motion is preferred in such cases. Forehand welding is most satisfactory. The welding rod can be fed either continuously or intermittently. To avoid undue oxidation, it should not be withdrawn from the protective atmosphere of the gas shield during welding. Vertical, horizontal and overhead welds can be made in magnesium alloys with

Table 6—Data for Manual Inert-Gas Metal-Arc Welding of Magnesium Alloys

Material Thickness, In.	Number of Passes	Welding Current,[a] Amp. AZ31X Alloy	Welding Current,[a] Amp. M1 Alloy	Electrode Diameter, In. A.C.	Electrode Diameter, In. D.C.	Welding Rod Diameter, In.	Gas Flow, Cu. Ft./Min. Argon	Gas Flow, Cu. Ft./Min. Helium
Sheet Material								
0.040	1	35	45	3/32	3/32	1/8	0.2	0.4
0.064	1	50	60	3/32	1/8	1/8	0.2	0.4
0.081	1	65	80	1/8	1/8	1/8	0.2	0.4
0.102	1	85	100	1/8	5/16	1/8	0.3	0.5
0.128	1	100	115	1/8	5/16	5/32	0.3	0.6
Plate Material								
3/16	1	140	160	3/16	5/16	5/32	0.3	0.6
3/16	2	100	100	1/8	5/16	5/32	0.3	0.6
1/4	1	180	200	3/16	3/8	3/16	0.3	0.8
1/4	2	115	125	1/8	1/4	5/32	0.3	0.6
3/8	1	250	270	5/16	...	3/16	0.4	0.8
3/8	2	140	160	3/16	5/16	3/16	0.3	0.8
1/2	2	310	330	1/4	...	3/16	0.4	0.8
3/4	2	420	450	5/16	...	1/4	0.6	1.2

[a] Current values given for welding with a backing plate, Table 5, and for making tee and lap joints. Slightly lower current values used for welding without a backing plate and for making corner or edge joints.

about the same technique as used on steel and aluminum.

Control of distortion may present a problem due to the high coefficients of thermal expansion and conductivity of magnesium alloys and their appreciable softening at welding temperatures. Rigid jigging, small beads, chilling and selected sequence of welding assist in controlling distortion as in welding other metals. Magnesium parts can be readily straightened after welding by clamping and holding in position while being heated to temperatures from 300 to 400°F. It is common practice to combine straightening operations with stress-relief heat treatments as discussed in a later section on stress relieving. If local torch heating is used for straightening, care must be taken so as not to overheat the material and destroy its properties. The temperatures recommended for stress relieving should not be exceeded.

If cracking is encountered it can be eliminated by factors which tend to increase the weld cooling rate and decrease the weld shrinkage. Lower melting point and lower shrinkage filler metal, smaller weld beads, faster welding speeds and jigging are beneficial. Welds in hot-short alloys should be started away from the end of the seam to avoid cracking. Sometimes welds located close to a sharp bend are more apt to crack than those located outside of an area previously deformed. In the high-calcium-bearing *AZ31X* sheet, it is possible that the residual stresses remaining from previously deposited welds may make it difficult to repair or deposit subsequent welds located in close proximity to the original weld without first stress relieving.

Cleaning of arc welds merely requires wire brushing to remove the slight oxide deposit on the surface. Structures and parts are then ready for either a chrome-pickle or dichromate treatment followed by painting if desired. For some industrial applications, no additional surface treatment is necessary. Arc welds in magnesium alloys other than *M1* alloy are sensitive to stress corrosion cracking unless relieved as recommended in the section on stress relieving.

Machine Welding.—Practically the same procedures employed in manual welding apply to machine welding, except for the higher currents and faster speeds generally used. Speeds up to 80 in. per min. can be used on thin gage sheet; however, speeds of 6 to 20 in. per min, are more common. Data given in Table 7 can be used as a guide for determining settings for automatic welding.

An important factor in machine welding is the proper and constant alignment between the electrode and welding rod. The welding rod should be fed into the arc at a low angle to the work so that it touches the weld surface immediately ahead of the electrode. Automatic arc-voltage control can be used in welding with d.c. when helium is used for shielding. In this case, an operating arc-voltage control setting of about 18 volts should be used. When using argon, a preset arc length has to be used because of the unsatisfactory arc-voltage vs. arc-length relationship at arc voltages above 15 or 16 volts. A preset arc length is generally used for machine welding with alternating current.

Properties of Arc Welds.—Typical strength properties of butt welds in mag-

Table 7—Data for Automatic Inert-Gas Metal-Arc Welding[a]

Material Thickness, In.	Welding Current,[b] Amp.	Welding Speed,[b] In./Min.	Electrode Diameter, In. A.C.	Electrode Diameter, In. D.C.	Welding Rod Diameter, In.
0.040	55	20	3/32	1/8	3/32
0.064	75	18	3/32	1/8	3/32
0.081	95	17	1/8	3/16	3/32
0.102	115	16	1/8	3/16	1/8
0.128[c]	150	14	1/8	1/4	1/8
0.188	250	12	3/16	...	1/8
0.250	350	10	1/4	...	1/8
0.375	450	8	1/4	...	5/32
0.500	550	6	5/16	...	5/32

[a] Data for machine welds made on square butt joints with backing plates and holddown bars. Gas flow slightly greater than that used for manual welding of equivalent material thicknesses because of faster welding speeds.

[b] Current values and welding speeds only approximate for welding *AZ31X* and *M1* alloys. Lower welding currents and slower speeds may be more desirable when welding with d.c.

[c] Maximum thickness recommended for welding with d.c.

nesium alloy sheet, plate, extrusions and castings are given in Table 8. The values given are for welds with the weld bead reinforcements left on. Except for *M1* alloy, the tensile strengths of arc welds are usually better than 90% of the strength of the annealed parent metal. Lower weld joint efficiencies are obtained in hard-rolled sheet because of the annealing effect from welding. There is no appreciable difference between the properties of welds made with direct or alternating current.

Table 8—Typical Strength Properties of Inert-Gas Metal-Arc-Welded Butt Joints

Material	Welding Rod	Tensile Strength, Psi	Elongation, % in 2 In.	Joint Efficiency, %
		Sheet and Plate		
M1(A)	M1	20,000	2.0	60
M1(H)	M1	22,000	1.5	60
AZ31X(A)	AZ61	36,000	12.0	97
AZ31X(H)	AZ61	37,000	10.0	86
		Extrusions		
M1	M1	20,000	2.0	55
AZ31X	AZ61	35,000	12.0	92
AZ61X	AZ61	40,000	8.0	91
AZ80X	AZ92	42,000	4.0	91
		Castings		
AZ63[a]	AZ63	28,000	3.0	70
AZ92[a]	AZ92	28,000	3.0	70

[a] Heat treated and aged.

As a general rule, arc welds made between dissimilar magnesium alloys result in joint strengths approximately equal to those obtained in the alloy which has the lower weld strength.

Peening increases weld strengths slightly but is seldom warranted because of the danger of overpeening and cracking. If welds are to be peened, they should be heated to temperatures of 300 to 400°F. Aging of welds in *AZ80* alloy extrusions will increase weld strengths about 5 to 10%. However, such aging is not too practical because of the long treatment time, 12 hours at 350°F. There is some improvement in weld strengths through the use of higher alloy content filler metal, especially when the weld beads are ground flush. Welds made in *AZ31* alloy sheet material with *AZ61* or *AZ92* rod have strengths 2000 to 3000 psi. higher than those made with *AZ31* rod. The temperatures and heating cycles recommended for stress relieving do not affect the strength properties of the welds.

Data available on the fatigue strength of arc welds in magnesium alloys are quite limited. A fatigue limit of 10,000 psi. has been obtained for butt welds in *AZ31* alloy sheet, and 6000 psi. in *M1* alloy sheet. These values are based on tension-tension type fatigue strengths at a minimum to maximum stress ratio of 0.25 and 10 million cycles, with the weld bead reinforcements left on. The same limits for the unwelded sheet alloys are 18,000 and 15,000 psi., respectively.

On long-time exposures in normal atmospheres, inert-gas metal-arc welds show little sign of corrosive attack. Small particles of tungsten inclusions in the weld will not affect the corrosion resistance nor do they show a detrimental effect on weld properties. They are extremely hard, however, so that high-speed machining or shearing of arc welds is not recommended.

Gas Welding

M1 alloy in the form of sheet, extrusions or castings is the most suitable magnesium alloy for gas welding. Welding of the alloys having a wider solidification range is less satisfactory from the standpoint of sagging, cracking or possible flux entrapment. Because of the corrosiveness of the flux used, gas welding is restricted almost exclusively to simple butt and corner joints in which all traces of flux can be completely removed after welding. Gas welding has been used mostly in the manufacture of magnesium aircraft oil and fuel tanks. In such applications, it has the advantage over arc welding in that fit-up and jigging requirements are less critical.

Welding Torches and Gases.—Torches used for gas welding magnesium are usually of the small aircraft type. The welding gases most commonly used are

oxy-carbohydrogen and oxy-acetylene. Carbohydrogen gas, composed of about 80% hydrogen and 20% methane, is well suited for welding sheet up to 0.064 in. because of its soft flame. For welding heavier gages, acetylene is more desirable because of its hotter flame. The oxy-acetylene flame is apt to cause slight pitting of the weld surface, but pitting is never so serious as to impair the strength properties of the weld.

Welding Fluxes.—Proprietary fluxes specifically recommended for gas welding magnesium should be used. These fluxes are usually supplied as dry powders in hermetically sealed glass bottles and are prepared for use by mixing with water to form a heavy slurry or paste. Only enough for one day's use should be mixed at a time, and the paste should be kept in covered glass containers when not in use. The flux paste can be applied to the work and welding rod with a small bristle brush or, when possible, by dipping into the flux.

The purpose of the flux is to protect the heated and molten metal from excessive oxidation and to remove any oxidation products on the surfaces. It should promote proper fluidity and wetting action between the weld metal and base metal without any serious attack on the magnesium. Most of the fluxes do not react with magnesium in the fused state but do react strongly after taking on moisture. Because of this, all traces of flux and flux residues must be removed soon after welding.

One flux composition which can be satisfactorily used on magnesium for welding with oxy-carbohydrogen, oxy-acetylene or oxy-hydrogen consists of 54% KCl, 30% $CaCl_2$, 12% NaCl and 4% NaF. Another composition suitable only for oxy-acetylene welding consists of 46% KCl, 26% NaCl, 24% LiCl and 4% NaF. This latter flux composition is more active than the former and will result in more surface pitting when used with gases containing appreciable quantities of hydrogen.

The presence of large amounts of sodium in the welding flux gives an intense glare to the welding flame. Consequently, most welding operators prefer to use special blue filter lenses.

Base-Metal Preparation.—Cleaning of magnesium surfaces for gas welding should be as thorough as for arc welding. A bright-chrome-pickle treatment, steel wool, abrasive cloth or power wire brush are recommended for cleaning. Chrome-pickled material can be gas welded without the removal of the pickle coating, but this is not advised because of the reduction of chromates and lowering of the corrosion resistance of the weld.

Typical gas-welded joints used on magnesium aircraft oil tanks are shown in Fig. 2. Cast and extruded fittings should be tapered at their edges to approximately the same thickness as the sheet to which they are to be welded. *M1* alloy sand cast fittings may sometimes have very fine cracks around the periphery of the flanges not visible until the casting is heated or welded. These fittings should be cast with slightly larger flanges than necessary and the flanges machined to the desired thickness and diameter for welding. Beading of the sheet around the opening for the fitting will reduce buckling. Weld joints should be located on corners and curved surfaces as much as possible to minimize distortion.

Assemblies are usually tack welded in a jig and then removed for final welding. Plenty of freedom should be allowed for the expansion and contraction of parts in the jig. Fittings should be held on pins or rods so that they are free to move with the sheet while welding.

Welding Technique.—A liberal coating of flux should be applied to both sides of the weld seam and onto the welding rod. Tack welds should be about $^3/_8$ in. in size and spaced at 1- to 3-in. intervals depending upon sheet thickness. In making a tack weld, the weld area is preheated gently with the outer flame of the torch to gradually dry and fuse the flux. Too harsh a flame may blow the flux away. After the flux is fused, the inner cone of the neutral flame is brought to within $^1/_{16}$ to $^1/_8$ in. of the work and a drop of metal added from the rod. The seam may require fluxing again before completing the weld.

The weld proper should start in the same manner as for tacking. Welding should progress in a straight line at a uniform rate of speed with the torch inclined at an angle of about 45 deg. with the work. The torch should be moved steadily while the rod is dipped intermittently into the weld puddle. To allow for accumulation of heat, it is best

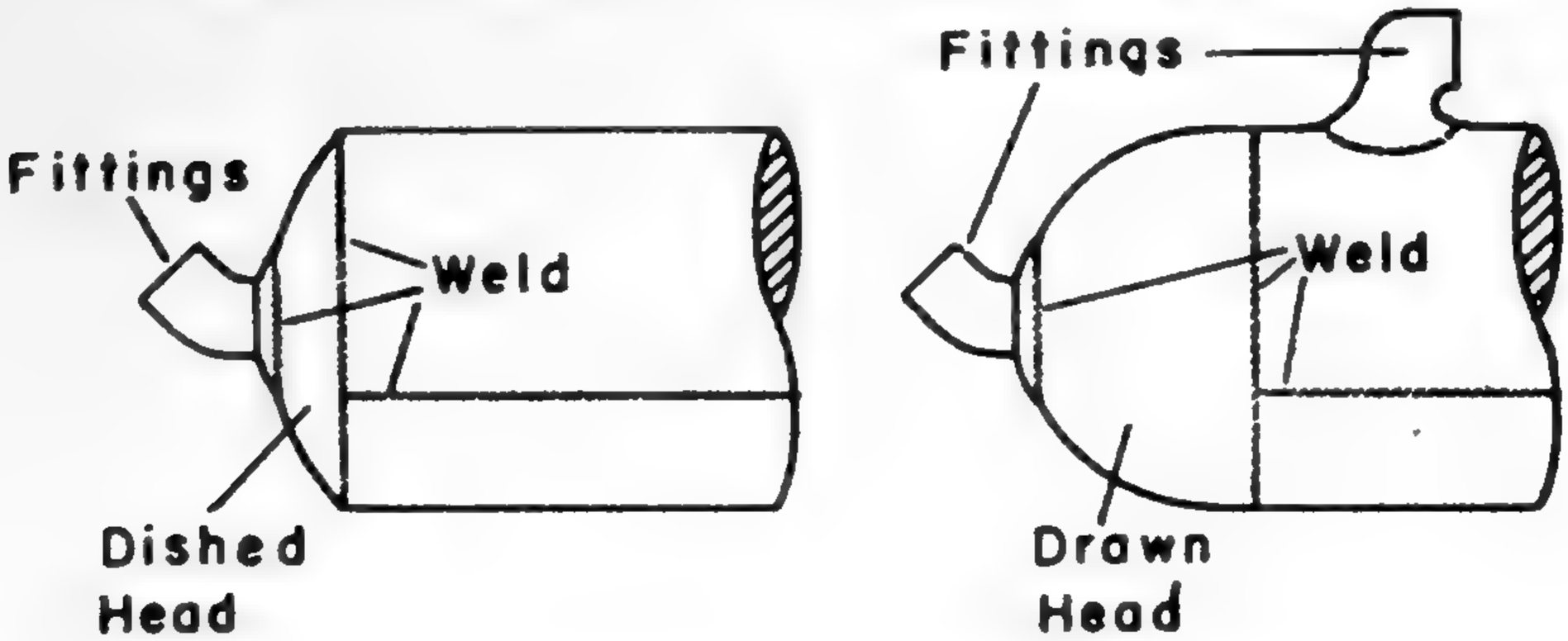

Fig. 2.—Joint Designs for Gas Welding

to decrease the angle of the torch and to increase the speed rather than lift the torch from the work. Too hot a flame or too slow a speed increases the activity and viscosity of the flux and causes pitting.

If a weld is interrupted, the end of the weld should be refluxed, and the flame directed slightly ahead of the weld before restarting the bead. All tack welds and overlapping welds should be remelted to float out any flux inclusions. To avoid cracking at the start, the weld should be started away from the edge. Some puddling with the rod may be necessary to get the metal to begin flowing properly. Fittings should be preheated before attempting to weld in place.

All traces of flux must be removed from parts after welding by first washing in hot water and then giving a chrome-pickle and dichromate boil (see Table 4). Soft leather or wood mallets can be used for aligning edges and for straightening after welding. Large or sharp deformation should never be hammered out without heating the area to 400 to 600°F. Gas welded *M1* alloy does not require stress relieving after welding to avoid stress corrosion cracking. Stress relieving may be desirable, however, for dimensional stability or improved serviceability.

Properties of Gas Welds.—Strength properties of gas welds in *M1* alloy sheet are usually lower than those of arc welds. This is due to the more extensive heated zone and the slower heating and cooling rates obtained. The average tensile strength of *M1* alloy gas welds is about 18,000 to 20,000 psi. The weld strengths are largely affected by the size of the weld bead, medium sized beads being most desirable. Peening may be used to increase the weld strengths but should be done around 500°F. to avoid cracking. Provided all traces of flux have been removed, the corrosion resistance of gas welds will equal that of arc welds.

Spot Welding

Spot welding is being used on magnesium alloy sheet and extrusions in thicknesses up to about $^{3}/_{16}$ inch. The alloys most commonly spot welded are *AZ31X* and *M1*. Spot-welded magnesium assemblies are used mostly for low-stressed applications, and occasionally for high-stressed applications not subject to excessive vibration.

Spot welding of magnesium alloys is similar to the spot welding of aluminum alloys. Careful preweld cleaning, preferably chemical, is essential for the production of consistently sound welds. An electrical surface resistance of 50 microhms or less is necessary for best welding conditions. Properly chemically cleaned sheet (Table 4), will maintain a low and consistent surface resistance for at least 100 hours; whereas surfaces cleaned with steel wool or a fine abrasive cloth will develop progressively higher and more inconsistent resistances after about 8 to 10 hours. Mechanically cleaned material should be spot welded immediately after cleaning for best results.

Because of the relatively high thermal and electrical conductivities of magnesium alloys, high current and short weld durations are required in spot welding. Both a.c. and d.c. spot welders of the types used on aluminum have sufficient capacity and provide adequate control of current and pressure for welding magnesium. As in welding aluminum, a very rapid electrode follow-up is required to maintain pressure on the weld while the metal is in the soft plastic range. Pneumatic operation of the pressure mechanism is preferred because of the rapid follow-up and accurate pressures provided. The additional forging pressure as sometimes used on aluminum alloys to prevent cracking while the weld cools is apparently not required nor beneficial in the spot welding of magnesium alloys. In general, satisfactory spot welds can be made in magnesium with lower pressures than required on aluminum which allows for the use of smaller flanges and closer edge spacing, and also the use of smaller offset electrodes for welding in confined areas.

Spot-Welding Equipment.—Alternating current spot-welding machines equipped with electronic synchronous timers and heat control and phase shifting devices to control weld timing and current are suitable for use on magnesium alloys. The line demand with this type of equipment may be as high as 500 kva. when spot welding sheets of approximately 0.128 in. thickness. Typical currents, pressures and weld-time cycles used for spot welding various commonly used gages of *M1* and *AZ31X* alloy sheet are

given in the *Recommended Practices for Resistance Welding* in Chapter 16.

Of the stored-energy type machines, the electrostatic condenser discharge machines are the most widely used on magnesium alloys. The line demand with this type of equipment is less than that with a.c. equipment, requiring only about 100 kva. for the welding of 0.128-in. sheet. The condenser capacity will vary from 600 to 2400 microfarads for welding sheet up to about 0.128 inch. Best results are obtained with high turns ratios, 480 to 1, where the time to peak current will be around 10 to 20 milliseconds. Except in certain cases, it is desirable that condenser discharge machines provide a means for reversal of current direction or change in electrode polarity for alternate welds. Machine settings vary considerably between different welders. The values given in Chapter 16 will serve as a guide for the spot welding of *M1* and *AZ31X* alloy sheet.

Electrodes.—Electrodes for spot welding magnesium alloys should be made from high-conductivity copper alloys conforming to RWMA, Group A, Class 1 specification. Hard-rolled pure copper can be used where special offset electrodes are desired. Electrodes should be water cooled to within about 3 in. of the tip, but should never be cooled below the dew-point temperature where condensation takes place. Intermittent water flow supplied only when a weld is made assists in maintaining constant tip temperature Dome-shaped tips are most common with tip radii ranging from 2 to 6 in. depending upon the sheet thickness. The 4-deg. flat tips are also frequently used. Flat tips with diameters from $^{3}/_{8}$ to $1^{1}/_{4}$ in. are used on one side of the work where surfaces are to be essentially free from marks. Conical tips are seldom used because of the problem of maintaining their shape and since no advantage is gained in their use. Contact surfaces of the electrodes must be kept clean and smooth.

Factors Affecting Welding Conditions.—Spot-welding conditions vary somewhat with the type of alloy welded. *M1* alloy requires much higher current for spot welding than either *AZ31X* or *AZ61X* alloys. It is also desirable to use a longer weld time when welding *M1* alloy. The electrode force required generally increases with the strength and hardness of the alloy, that is in the order *M1*, *AZ31X* and *AZ61X*.

Although satisfactory welds can be produced over a fairly wide range of current values only those values in the middle of the range between *dud* and expelled or cracked welds should be used to obtain maximum consistency. *Dud* welds made at low weld currents may have fair strengths due to pressure bonding, but they usually fail suddenly and have erratic strength properties. At high weld currents a limit is reached where expulsion occurs. The maximum current can be increased by increasing the electrode pressure or electrode tip size. Other conditions being constant, increase in pressure will increase the current necessary for a weld of a given strength, widen the range of current in which sound welds can be made and decrease the cracking tendency at high-current values. An increase in weld time will decrease both the current necessary for welds of a given strength and the tendency for cracking of large unexpelled welds, and, up to a certain limit, increase the maximum size and strength of welds. Too short a weld time gives more concentrated heat resulting in smaller and weaker welds with greater chances for cracking, expulsion and porosity.

Tip life is limited either by the appearance of copper on the surface of the weld or by the sticking of one or both of the electrodes to the work. It is mostly dependent upon the surface preparation, type of alloy, current and cooling of electrodes. Under the best conditions of chemically cleaned surfaces no more than about 25 sound welds can be expected in *M1* alloy before tip cleaning becomes necessary. With *AZ31X* alloy, about 100 to 200 consistently sound welds can be made between tip cleanings. Water cooling greatly improves tip life and should always be used. Better tip life is obtained when small or medium sized welds rather than large welds requiring high currents and pressures are being produced. Copper pickup on the magnesium increases the corrosion susceptibility of the weld. Copper deposits should be completely removed either with steel wool or with a fine abrasive compound on a polishing wheel. A positive check can be made to assure complete removal of copper by applying a 10% acetic acid solution to the weld and wiping with

a cloth. A dark spot will remain if there is any copper on the surface.

One other criterion which affects maximum tip life when spot welding magnesium alloys with d.c. stored energy equipment is the number of welds which can be made before excessive displacement of the weld occurs. There is a definite polarity effect due to current flowing in one direction. More heat is liberated and consequently more rapid pickup occurs at the positive electrode, which progressively increases with the number of welds made. As a result, displacement of the weld nugget into the sheet next to the positive electrode may occur before other indications of tip fouling are evident. For this reason, d.c. equipment should provide reversal of weld current direction for each successive weld to extend tip life and checks should be made by sectioning to determine the number of welds which can be produced between tip cleanings before excessive weld displacement occurs.

Pressures are usually established first using the lower currents or condenser capacitance and voltage values recommended. High pressures provide greater latitude in the currents which can be used for the production of sound welds but may be limited by excessive sheet separation and deflection of small offset electrodes. After approximating the pressure, the proper weld current and weld time or condenser capacitance and voltage should be determined to obtain the required size and strength welds. If the maximum weld size or strength is too low or cracking is encountered, it may be necessary to increase the pressure and current again, or possibly the weld time. After all other settings are fixed, it may be necessary to adjust the hold-time to make certain that pressure is maintained on the weld until solidification is complete. Insufficient hold-time will result in porous welds and is normally indicated by a *cracking* sound during the contraction of the weld.

Trial welds should be made on material of the same gage, alloy, hardness and surface preparation as the material to be welded. Welds made between two crossed strips are useful for deriving proper welding conditions since the welds can be easily twisted apart by bringing the ends of the strips together. Shear tests should be made after all other conditions of soundness have been met such as freedom from porosity, cracks, expulsion or excessive sheet separation.

Weld penetration as well as the diameter of the fused weld zone can be ascertained by sectioning the weld through the center, polishing and then etching with about a 10% acetic acid solution. The penetration should not be less than 30 nor more than 80% into each of the parts welded nor should there be any excessive displacement of the weld into one part. If welds are appreciably displaced. subsequent welds may require the use of a smaller electrode against the side with the least penetration, or it may be necessary to clean the electrodes more frequently or the material surfaces more thoroughly.

When welding unequal sheet thicknesses together, an electrode with a larger contact area should be used against the thicker material. If this is not done, a weld with no penetration or insufficient penetration into the thinner sheet may result. Machine settings and weld diameters are usually based on the thickness of the thinner sheet. In welding more than two sheets together, the machine settings for current and pressure are slightly higher than when welding two sheets equal to the total thickness. To eliminate tip indentation, a flat tip may be used against the part which is not to be marked. Sheet up to 0.064 in. thick can be welded in this manner without appreciable displacement of the weld.

In attempting to weld dissimilar alloys, differences in properties such as thermal conductivities and electrical resistivities can be compensated for by using a smaller tip in contact with the sheet which requires the greatest heat input to weld. For example, to keep the weld nugget centered in a joint between equal gages of *M1* and *AZ31X* alloy sheet, a smaller tip should be used against the *M1* alloy sheet.

After welding, spot-welded assemblies can be given either a chrome-pickle or dichromate treatment (Table 4) followed by painting and finishing as desired. Where sealed joints are required, or where parts are to be placed in service in a very corrosive atmosphere, a semi-liquid compound should be used between the faying surfaces of the joint. There are many suitable compounds available for this purpose. They should not be so

viscous as to prevent bare metal contact when pressure is applied. Welds should be made soon after applying the compound and frequent tests made to check weld strengths. Assemblies with sealed joints should not be subjected to surface treatments involving boiling solutions, nor exposed to prolonged periods of heating because of the tendency for the compound to bleed out of the joint.

Properties of Spot Welds.—Typical and minimum single shear strengths specified for spot welds in various gages of *M1* and *AZ31X* magnesium alloy sheet are given in Chapter 15. Although higher shear strengths are readily obtainable, these values represent the average strengths obtainable when welds of maximum soundness and consistency are produced. Shear strengths of welds in *AZ61* alloy are practically the same as in *AZ31X* alloy. Aging of spot welds in *M1* alloy for two hours as 600°F. will increase the shear and tension strengths almost 50%. Spot welds in thin gage magnesium sheet, below about 0.040 in., usually fail by tearing a button from the sheet. In thicker sheet, weld failures approach more perfect shearing through the weld nugget.

Service experience has shown that faying surfaces of spot-welded joints in magnesium alloys seldom require any special protection. Usually, only a thin gray film of magnesium hydroxide is formed at the faying surfaces. Accelerated tests in 3% sodium chloride show drastic attack, but there is little correlation between these results and actual service. Assemblies requiring maximum protection at the faying surfaces should be dip painted in preference to spraying, or sealed with a suitable compound at the faying surfaces. No evidence has been reported to indicate that spot welds in magnesium alloys are subject to stress corrosion cracking in service.

Design of Spot-Welded Joints.—The designs used for spot welding magnesium alloys are much the same as those used on aluminum alloys, except that closer edge distances are permissible. Minimum recommended dimensions for location of spot welds are given in the *Recommended Practices* in Chapter 16.

Where unequal thicknesses of magnesium sheet are to be spot welded, the thickness ratio should not exceed $2^1/_2$ to 1 if maximum consistency and high weld strengths are to be obtained. It is possible with d.c. equipment to make satisfactory spot welds between greater differences in thickness, such as 0.091-in. sheet to $^3/_8$-in. sections, by holding the thicker section against the positive electrode. In welding three pieces together, it is best that the thicknesses do not vary more than about 25% of each other. It is also best to have the thickest section in the center.

Spot-welded joints should be avoided where they will be subjected to excessive vibration. Fatigue strengths of spot-welded joints are slightly lower than those of riveted joints and much lower than those of either arc- or gas-welded joints. The welding of dissimilar alloys should also be avoided especially between alloys of markedly different properties.

Welding Castings

Inert-gas metal-arc welding is generally recommended for the welding of magnesium alloy castings. Welding is usually limited to the repair of defects in clean metal such as broken pieces, sand holes, blow holes, misruns, cracks, cold shuts, and mutilations due to mismachining, chipping, sawing or grinding. It is not recommended for use in areas of gross porosity, oxide or flux inclusions, or where castings have been previously impregnated with an organic material to obtain pressure tightness, or where castings may contain oil in the pores. Many castings are used as integral parts of aircraft structures and depend upon heat treatment for increased strength. Unless suitable facilities for reheat treatment are available the welding of these castings is not recommended.

Before welding castings, several factors should be taken into account such as type of alloy, previous thermal treatment, size and intricacies of sections, and location of welds with regard to degree of restraint or freedom for expansion or contraction. Alloy composition can usually be identified by designation markings on the castings. If not, a chemical or spectrographic analysis should be made. *AZ63* and *AZ92* castings in the as-cast condition may be differentiated from each other by the color of the chrome-pickle deposit. On *AZ63* this deposit has a matte iridescent appearance, much lighter than the gray deposit found on *AZ92* castings. On *M1* alloy, the deposit is

much brighter and brassier than on either of the other alloys.

Castings can be welded in the as-cast, solution heat-treated, or solution heat-treated and aged conditions. Some magnesium foundries prefer to weld castings only in the solution heat-treated condition whereas others contend that less cracking is encountered when castings are in the as-cast or solution heat-treated and aged conditions. It is desirable to know the heat-treated condition before welding since this will somewhat affect the preheating for welding and heat treatment of castings after welding. The recommended heat treatments for *AZ63* and *AZ92* castings are given in Table 9.

slight local preheat of 300 to 500°F. may be sufficient. Care should be taken in local preheating so as not to overheat the metal and damage its properties.

An air-circulating furnace with a temperature control of ±10°F. at preheat temperature is recommended for preheating. No special atmosphere is required; however, a temperature limit control set at 10°F. above the preheat temperature should be used in case of failure of the other controls. The recommended preheat temperatures for *AZ63* and *AZ92* alloy castings are given in Table 9. Solution heat-treated or solution heat-treated and aged castings can be charged to a hot furnace at preheat temperature

Table 9—Heat Treatment of Castings After Welding (AZ63 and AZ92 Alloys)

Alloy[a]	Desired Condition After Welding	Condition Before Welding	Heat Treatment After Welding
AZ63	Stress relieved	As-cast or heat treated	1 hr. at 500°F.
	Solution heat treated	Solution treated or aged[b] as-cast	1/2 hr. at 730°F.[c] 10 hr. at 730°F.
	Heat treated and aged	Solution treated or aged as-cast	Solution heat treat as above followed by aging 10 hr. at 360°F.
AZ92	Stress relieved	As-cast or heat treated	1 hr. at 500°F.
	Solution heat treated	Solution treated or aged[b] as-cast	1/2 hr. at 770°F.[c] (see below)[d]
	Heat treated and aged	Solution treated or aged as-cast	Solution heat treat as above followed by aging 10 hr. at 420°F.

[a] Preheat temperature for *AZ63* castings 725 ± 10°F., for *AZ92* castings 750 ± 10°F.

[b] Solution heat treatment of as-cast castings consists of preheating at a rate not exceeding 150°F. per hr. from 500°F. to heat treat temperature, followed by 10 hr. at 730°F. for *AZ63* alloy, and 6 hr. at 770°F., 2 hr. at 670°F. and 10 hr. at 770°F. for *AZ92* alloy, then air cool. SO_2 atmosphere in furnace.

[c] Solution of compound in weld metal obtained in 15 to 30 min. Welded *AZ63* castings can be given standard 10 hr.-solution treatment without danger of germination in welds. Welded *AZ92* castings should not be heat treated for longer than 30 min. to avoid germination in welds.

[d] Special heat treatment consisting of slow preheat, 4 hr. at 775°F., cool to 200°F. outside furnace or 400°F. inside furnace with doors open and return to 775°F. in 2-hr. period, 4 hr. at 775°F. This cycle is repeated three times.

Castings should be stripped of paint and degreased before welding. Pickle treatments can be removed from defective areas with steel wool or power wire brush. A hand routing tool is recommended for removing defects and preparing for welding. Broken pieces can be held in position by clamps or other means and should be beveled at the fracture similar to the preparation for arc welding wrought alloys. Where large holes or defective areas are to be filled in with weld metal, the use of a magnesium or steel backing plate may be advantageous to avoid excessive dropping through of the weld metal.

Preheating.—Most magnesium castings require the use of preheat to avoid weld cracking. In some cases where welds are to be made in relatively unrestrained areas, such as on external bosses or flanges, preheating is unnecessary or a

without damage to the casting. As-cast castings should not be charged in a furnace above 500°F. and should be heated to the preheat temperature at a rate not exceeding 150°F. per hour above 500°F. to avoid incipient fusion of Mg-Al and Mg-Al-Zn compounds. Castings should be allowed to remain at preheat temperature for a sufficient period of time to assure uniform heating throughout. After castings are removed from the furnace, welding should proceed immediately and be discontinued after the temperature of the casting has dropped below about 600°F. A casting weighing from 50 to 100 lb. can usually be welded within a period of about 4 or 5 min. after removal from furnace before its temperature has fallen below 600°F.

Welding Technique.—Defects in castings are welded in much the same manner as used in welding wrought alloys.

Welding currents from 50 to 100 amp. are normally used. Welding of broken pieces should commence at the center of the break and progress toward the outer ends. Medium size weld beads are preferred. Too little heat will result in porous welds whereas too much heat may cause cracking or voids in the parent metal. The filling of holes is usually the most critical repair from the standpoint of cracking. The arc should be struck at the bottom of the hole and welding progressed upwardly. Care must be taken not to dwell too long in one area, since this makes the weld more susceptible to cracking and the formation of voids in the base metal.

When the temperature of the casting falls below 600°F., the casting should be returned to the furnace for reheating before completing the repair. Many castings can be cooled in still air at ambient temperatures after welding without danger of cracking. If of especially intricate design, the casting may require slow cooling in either a previously warmed soaking box or pit.

Excess metal can be easily removed from welds by means of a routing tool. Welds can then be examined for soundness by visual, radiographic or fluorescent penetrant inspection. Visual inspection with a magnifying glass is very satisfactory for detecting small cracks in or around the welds after etching the area with a 10% acetic acid solution. Normal radiographic methods producing a sensitivity of 1 to 3% are satisfactory for detecting most critical defects such as incomplete penetration, gross porosity and cracks, provided the cracks are not extremely small or in sections greater than about 1 inch. Fluorescent penetrant inspection is not too satisfactory because of the number of spurious indications which make a sound weld appear unsatisfactory.

Heat Treatment After Welding.—Repaired castings are generally heat treated again after welding although satisfactory properties can be obtained without additional heat treatment. The heat treatments, as given in Table 9, depend upon the condition of the castings before welding and the desired condition after welding. If complete solution heat treatment is not desired, welded castings should be stress relieved. Because of the small grain size and fine dispersion of Mg-Al and Mg-Al-Zn compounds in the weld metal, a short heat treatment time of 30 min. is sufficient to obtain complete solution of the compounds in the weld. Only the minimum heat treatment time necessary for complete solution should be used for welded *AZ92* castings because of the susceptibility of the weld metal in this alloy toward germination.* Typical strength properties of welds in heat treated and aged *AZ63* and *AZ92* castings are given in Table 8.

Brazing

Brazing is being used in joining magnesium alloys with techniques similar to those used on other metals, except for the temperatures, filler metal and fluxes used. The three brazing processes employed are furnace, flux dip and torch brazing. These processes have been most effectively applied to *M1* alloy because of its high melting point and the relatively high temperatures required in brazing. The filler material is a magnesium base alloy so that the characteristics of the brazed joint are similar to those of a welded rather than a soldered joint. *AZ92* alloy, either of the commercial grade or with a small amount of beryllium added, is used as the filler material. The beryllium addition is necessary only in furnace brazing to avoid possible ignition of the magnesium.

For torch and chemical dip brazing, chloride base fluxes similar to those used in gas welding are suitable. The dry powder or a paste of flux mixed with alcohol can be used for torch brazing. In furnace brazing, a slightly modified flux is required. A paste made with organic compounds such as benzene, toluene or monochlorobenzene gives best results. Alcoholic or water pastes are unsuitable for furnace brazing.

Brazing Procedures.—In furnace brazing, the parts are assembled with filler metal preplaced in or around the joints Clearances in joints are of importance in allowing the filler material to flow into the joints. They will normally vary from 0.004 to 0.010 inch. Steel fixtures are suitable for holding parts in place while brazing. The joints are fluxed and the assembly placed in a furnace heated to the proper brazing temperature. The brazing temperature for *M1* alloy is 1130

* Excessive grain growth resulting in the formation of abnormally large grains from smaller grains.

to 1160°F. It is recommended that limit controls be used which will prevent exceeding the maximum allowable temperature of 1180°F. No special atmosphere is required in the furnace to prevent ignition. Excluding the time to reach temperature, the brazing period should be of about 2 or 3 min. duration.

In dip brazing, the parts are assembled in a fixture with the filler metal in place and then dipped into a molten flux bath held at the brazing temperature. Any recommended magnesium gas welding flux is suitable for dip brazing. The brazing time is shorter for this process than for furnace brazing because of the greater heat transfer to the parts. The same alloys and temperatures are used for this process as are used in furnace brazing.

Practically the same equipment and technique as used in gas welding are used in torch brazing. The filler metal can be placed on the joint and fluxed before fusing, or it may be added as a welding rod. Oxy-acetylene or natural gas and air are suitable gas combinations for torch brazing. For certain production applications the torch can be set up in a jig so that the flame impinges upon the joint when the parts are placed in the jig. Natural gas is well suited for this procedure because of its soft flame and less danger of overheating.

Removal of all traces of flux is of utmost importance. Brazed parts should be treated in the same manner as gas welded parts to remove all flux and flux residues (Table 4).

Brazed joints have fairly good strength properties since only lap and fillet-type joints are commonly used. In general, the strength of a brazed joint in *M1* alloy material will be equivalent to that obtained when *M1* alloy has been heated to temperatures of 1130 to 1160°F., and is about 15,000 psi. The corrosion resistance of brazed joints is the same as that of gas-welded joints and depends mostly on the complete removal of flux.

Soft Soldering

Magnesium and magnesium alloys can be soldered, but soldering is usually limited to the building up of surfaces rather than for joining because of the low strength and brittle joints obtained. Solders similar to those used on aluminum, containing approximately 60% tin and 40% zinc (M.P. 630°F.) can be used. Other solder compositions which are satisfactory include 60% cadmium, 30% zinc and 10% tin (M.P. 550°F.), and 90% cadmium and 10% zinc (M.P. 570°F.). Because of the marked difference in solution potentials between the solders and the magnesium, soldered joints are unsatisfactory in moist or corrosive atmospheres.

Surfaces should be cleaned to a bright metallic luster before soldering. The surfaces should then be heated to a temperature just above the melting point of the solder and the solder rubbed vigorously over the area to obtain a uniform tinned surface. A stiff wire brush or sharp steel tool assists in establishing a bond. A copper soldering iron can be used but should be used sparingly because of the alloying of the copper with the solder. A small torch is effective where more heat is required. Overheating should be avoided inasmuch as this increases the alloying of the solder with the base metal which results in more brittle joints. No flux is necessary and its use is not recommended.

Other Welding Processes

Other welding processes used commercially in fabricating magnesium alloys are, principally, seam and flash welding. Pressure welding has been used to a limited extent. Stud welding with magnesium studs has recently been tried and appears suitable for certain applications. Processes which have not been found satisfactory for welding magnesium alloys include shielded metal-arc welding and atomic hydrogen welding. Although welds can be made with coated magnesium electrodes, shielded metal-arc welding has been unsuccessful due to flux inclusions and considerable spatter. Atomic hydrogen welding results in porous welds.

Seam Welding.—Seam welds can be made in magnesium alloys under conditions similar to those required for spot welding. Either continuous or intermittent-type welds can be made which have strength properties comparable to those obtained in spot welds. Shear strengths of about 750 to 1500 lb. per linear in. of welded seam can be obtained in *M1* alloy sheet material from 0.040 to 0.128 inch. In *AZ31X* alloy sheet material,

strengths of seam welds are approximately 50% higher.

Flash Welding.—Practically the same type of equipment and techniques as used in flash welding aluminum alloys can be used on magnesium alloys. High current densities and extremely rapid movement of platen are required. Current cut-off should occur from about 5 to 10 cycles after upset. Special atmospheres, such as helium or argon, are not necessary to obtain satisfactory flash welds. Flash welds in *AZ31X* and *AZ61X* alloys give strengths of about 36,000 to 42,000 psi., respectively, with elongations of about 4 to 6%.

Pressure Gas Welding.—Welds can be made in magnesium alloys by the combination of high pressure and heat which results in a pressure bond between the parts presumably due to diffusion across the weld interface. Pressure welds can be made by placing zinc foil between the weld surfaces and diffusing the zinc under a pressure of about 7000 psi. while heated at approximately 670°F. Welds can also be made without the use of zinc foil using slightly higher pressures and temperatures. Adequate data on strength properties of pressure welds in magnesium alloys are not available.

Stress-Relief Heat Treatment

Stress corrosion cracking of welds in magnesium alloys is a phenomenon similar to that which takes place in other metals. Only the higher alloy content magnesium alloys such as *AZ31X* and *AZ61X* are susceptible to this type of cracking. Pure magnesium and low-alloy content alloys such as *M1* are non-sensitive to stress corrosion. Stress corrosion cracking, as encountered in welded structures, usually occurs in the area adjacent to the weld bead and has always been found to be transcrystalline. Residual stresses as high as 15,000 psi. have been measured around magnesium arc welds. There is no evidence that spot welds in any of the magnesium alloys are subject to stress corrosion cracking in service. The type of atmosphere seems to have little effect on the length of time before cracking occurs. Exposure tests fail to show any appreciable difference between rural, industrial or marine atmospheres. The length of time before cracking varies with the alloy and stress. Cracking will be delayed somewhat by painting; however, this does not assure crack-free service over long periods of time unless welds are stress relieved.

Stress relieving can be accomplished either in a furnace or with a torch. Furnace stress relieving is definitely to be preferred. The length of time and the temperatures necessary for the stress relief of welded structures to assure freedom from stress corrosion cracking are given in Table 10. When furnace stress relieving, jigs or fixtures should be used to hold parts in alignment while being heated to prevent distortion or to correct for any warpage present. Thermocouples should be attached to large structures to make certain that all sections reach the proper temperature. Heated platens can be effectively used for stress relieving sheet and plate where flat surfaces are essential. In torch stress relieving, a temperature-indicating device should be used to avoid overheating.

Table 10—Recommended Stress-Relief Heat Treatments for Inert-Gas Metal-Arc-Welded Magnesium Alloys

Temperature, °F.	Time at Temperature,[a] Min.	Sheet and Plate	Extrusions
300	60	AZ31h	.....
400	60	M1h[b]	AZ80 HTA
500	15	M1a, AZ31a	M1, AZ31, AZ61, AZ80

[a] Time to reach temperature calculated roughly at 1½ hr. per in. of material thickness using a minimum of 20 min. for thin gage material.
[b] Stress relief of *M1* alloy not required to assure freedom from stress corrosion cracking.

Table 11—Specifications Applicable to Welding Magnesium Alloys

Specification	Source	Title
AN-T-38a-2	Army-Navy	Tests; Aircraft Welding Operator's Certification
AN-F-44	Army-Navy	Flux; Magnesium Alloy Welding
AN-W-30	Army-Navy	Welding; Aluminum and Magnesium Alloys, Spot and Seam
AN-H-25-3	Army-Navy	Heat Treatment of Magnesium Alloy Castings; Process for
AN-I-26-1	Army-Navy	Inspection; Radiographic
AN-I-3Ca	Army-Navy	Inspection; Fluorescent Penetrant Method of
PW-5c	Navy	Welding of Magnesium Alloys; Process for
AN-R-25	Army-Navy	Rod; Magnesium Alloy Welding

COMMON APPLICATIONS

Welded magnesium alloys are in demand for many aircraft parts such as oil and fuel tanks, structural sections, control surfaces, fittings and brackets and aircraft seats. (See Chapter 55.) Magnesium castings are used extensively for aircraft engine castings which are salvageable by welding. Magnesium furniture made from thin-walled extrusion stock is usually fabricated by welding. Other applications include dockboards, conveyors, hand trucks, reels, containers, tanks, ladders and such articles where light weight is of particular advantage. Specifications applicable to the welding of magnesium are listed in Table 11.

BIBLIOGRAPHY

1. *Arc Welding of Magnesium Alloys,* W. S. Loose, A. R. Orban, The Welding Journal Res. Suppl., December 1942.

2. *The Spot Welding of Magnesium Alloys,* Report prepared by the Magnesium Subcommittee of the Aircraft Welding Research Committee of the Engineering Foundation, W. S. Loose, Chairman, The Welding Journal Res. Suppl., December 1943.

3. *Dowmetal Data Book,* The Dow Chemical Company, 1944.

4. *Tooling for Magnesium Welding,* K. L. Kime, Iron Age, August 31, 1944.

5. *Designing with Magnesium,* American Magnesium Corporation, 1945.

6. *Reclamation of Magnesium Castings by Helium Arc Welding,* B. L. Averbach, Metal Progress, June 1945.

7. *Progress in Heliarc Welding,* T. E. Piper, Automotive and Aviation Industry, August 15, 1945.

8. *Emergency Repair of Magnesium Parts by Gas Welding,* The Welding Journal, November 1945.

9. *The Spot Welding of Magnesium,* R. F. Tylecote, Welding, February 1946.

10. *Welding of Magnesium,* L. F. Pearsall, The Welding Journal, June 1946.

11. *Study of Electric Arc Welding Cavities in ASTM No. 4 Castings,* G. W. Kurachek, Light Metal Age, June 1946.

12. *Design and Fabrication of Welded Magnesium Tanks for Aircraft,* R. J. Cross, Light Metal Age, January 1947.

13. *Pressure Welding of Light Alloys Without Fusion,* R. F. Tylecote, The Welding Journal Res. Suppl., February 1947.

14. *The Chemical Surface Treatment of Magnesium Alloy Sheet for Spot Welding,* W. F. Hess, T. B. Cameron and D. J. Ashcroft, The Welding Journal Res. Suppl., March 1947.

15. *Optimum Welding Conditions and General Characteristics of Spot Welds in Magnesium Alloy Sheet,* W. F. Hess, T. B. Cameron and F. J. Winsor, The Welding Journal Res. Suppl., May 1947.

16. *Observations on Electrode Tip Pickup and Tip Life in the Spot Welding of Magnesium Alloy Sheet,* W. F. Hess, T. B. Cameron and R. A. Wyant, The Welding Journal Res. Suppl., August 1947.

17. *General Corrosion and Stress Corrosion of Spot-Welded Magnesium Alloy Sheet,* W. F. Hess, T. B. Cameron and D. J. Ashcroft, The Welding Journal Res. Suppl., September 1947.

CHAPTER 34

COPPER AND COPPER ALLOYS*

GENERAL PROPERTIES

General

THERE ARE A LARGE number of copper alloys produced, many of them for special purposes. This chapter covers only those wrought alloys which are commonly welded.

The information for each of the materials includes its chemical composition and physical and mechanical properties and is intended to be helpful in the selection of the material most suitable for any specific application.

Copper

Copper, commercially available as various types, may be classified in two major groups: oxygen-bearing copper and oxygen-free copper. In general, all types of copper possess the same characteristics; however, the presence of oxygen or impurities in the form of small amounts of phosphorus, silver and arsenic affect some mechanical properties, which may or may not be desirable.

Oxygen-Bearing Coppers.—This group includes fire-refined and electrolytic tough pitch copper. *Fire-refined copper* results from the processing of scrap copper or from the treatment of ores. It contains varying percentages of impurities from contamination of the ores or scrap copper used, as well as 0.02 to 0.05% oxygen in the form of copper-cuprous oxide eutectic.† These impurities have little effect on the general mechanical properties of the wrought copper but require care in welding to avoid porosity. *Electrolytic tough pitch* copper is the most important commercial type of copper available. It contains less impurities than fire-refined copper and because of this, has more uniform mechanical properties. The oxygen content is the same as that of fire-refined copper.

The copper-cuprous oxide eutectic is scattered more or less uniformly throughout the wrought metal and has no harmful effect on the general mechanical properties. It does make the copper susceptible to gas embrittlement when heated in a hydrogen or carbon monoxide atmosphere to 1300°F. and the effect is accelerated at temperatures above 1500°F.

Oxygen-bearing coppers are of medium strength, low hardness, tough, ductile and highly malleable provided the copper oxide is uniformly distributed. Both electrical and thermal conductivities are the highest of all copper alloys (see Table 1). These coppers are highly plastic through a wide range of temperatures and are hot worked commercially from 1200 to 1650°F. as well as cold worked. When heated above 1680°F. for prolonged periods, the copper oxide is rejected to the grain boundaries causing a major reduction in strength and making the metal both hot short and cold short. These coppers may be annealed at temperatures of 450 to 1500°F. depending on the properties desired. Annealing in a reducing atmosphere (hydrogen, carbon monoxide) should be avoided because it reduces the copper oxide to pure copper, producing voids or fissures (gassed copper) which make the copper too brittle for use. The presence of oxygen as copper oxide has no appreciable effect on the corrosion resistance of these coppers, which possess very good resistance to atmospheric and sea water corrosion and are substantially immune to the attack of a large number of industrial chemicals although they are

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† Commonly referred to as *copper oxide* or *oxides*.

Table 1—Wrought Copper

Type →	Electrolytic Tough Pitch	Oxygen Free	Deoxidized (Low Phosphorus)	Deoxidized (High Phosphorus)
Chemical composition, %				
Copper (Silver) Min.	99.90	99.90	99.90	99.90
Phosphorus	....	....	0.004–0.012	0.015–0.04
Electrical conductivity (volume), % IACS[b] at 68°F. (annealed)	101	102	98–100	75–90
Thermal conductivity at 68°F., Btu./ft.²/ft./°F./hr.	226	228	....	175–205
Melting range, °F.				
Solidus	1949	1981	1981	1977
Liquidus	1981	1981	1981	1981
Thermal expansion per °F., 68–572°F.	9.8×10^{-6}	98×10^{-6}	9.8×10^{-6}	9.8×10^{-6}
Specific heat at 68°F., Btu./lb./°F.	0.092	.092	0.092	0.092
Forms available (indicated by ASTM spec.)				
Plate, sheet and strip	B11[a], Grade 1; B152, Type A	B152, Type C	....	B11[a], Grade 2; B152, Type B
Rods, bars, and shapes	B12[a], B49; B124, Alloy 12; B133; B187	B12[a]; B49; B124, Alloy 12; B133; B187	B12[a]; B49; B124, Alloy 12; B133; B187	B12[a]; B124, Alloy 12; B133
Pipe and tube	B13[a]; B111[a]; B188	B13[a]; B68, Type D; B75[a], Type D; B111; B188	B13[a]; B42[a]; B68, Type A; B75[a], Type A; B88; B111[a]; B188	B13[a]; B42[a]; B68, Type B B75[a], Type B; B88; B111[a]
Wire	B1; B2; B3; B47; B48	B1; B2; B3; B47; B48	B1; B2; B47	...
Mechanical Properties				
Annealed				
Tensile strength, psi.	30,000–38,000	30,000–38,000	Substantially same as high phosphorus deoxidized	30,000–38,000
0.5% yield strength, psi.	7500–34,000	8000–17,000	Substantially same as high phosphorus deoxidized	10,000
Elongation in 2 in., %	45	36–41	Substantially same as high phosphorus deoxidized	25 45
Hard:				
Tensile strength, psi.	43,000–52,000	43,000–54,000	Substantially same as high phosphorus deoxidized	45,000–55,000
0.5% yield strength, psi.	43,000–48,000	46,000–53,000	Substantially same as high phosphorus deoxidized	50,000
Elongation in 2 in., %	5	4	Substantially same as high phosphorus deoxidized	8

[a] ASME specification with the prefix SB identical with this ASTM specification.
[b] International Annealed Copper Standard.

readily attacked by metallic salts susceptible to chemical reduction. Copper should not be used in contact with oxidizing acids and most oxidizing agents or in services where alternate exposure to oxidizing conditions and acid reagents are anticipated. Low concentrations of ammonia and carbon dioxide in water can also act as strong corrosive agents. Coppers are generally immune to stress-corrosion failures.

Oxygen-Free Coppers.—This group includes phosphorized copper and oxygen-free high conductivity copper. *Phosphorized copper* (phosphor deoxidized copper) is copper from which the oxygen has been removed by the addition of 0.01 to 0.04% phosphorus to the melt prior to casting. If the phosphorus addition is closely controlled to obtain less than 0.01% residual, the copper is called *high-conductivity phosphorized copper. Oxygen-free, high-conductivity copper* is copper from which the oxygen has been removed by the use of hydrogen as deoxidant. The copper is melted and cast in an atmosphere of hydrogen which reduces any oxides present and prevents the formation of oxides during the casting. Since no deoxidant remains in the cast copper, it can be internally oxidized by prolonged heating in air at elevated temperatures. A common designation for this type of copper is *OFHC copper.*

The oxygen-free coppers have the same general mechanical properties as the oxygen-bearing coppers but more uniformity of properties is obtained (see Table 1.) Because of the absence of copper oxide better fatigue resistance is obtained. As compared with oxygen-bearing copper, phosphorized copper containing less than 0.01% phosphorus has the same or slightly higher electrical and thermal conductivities whereas phosphorus copper, having from 0.01 to 0.05% phosphorus, has lower electrical and thermal conductivities. Both conductivities are greater for OFHC copper. Phosphorus coppers are highly plastic and possess no critical range in which plasticity is seriously reduced. With the absence of copper oxide the cold working of these coppers is slightly improved over that for oxygen-bearing coppers, particularly in deep drawing and spinning operations. These coppers can be annealed at temperatures between 450 to 1500°F. depending upon the properties desired; they can be annealed in reducing atmospheres since no gassing or embrittlement occurs. The corrosion resistance of these coppers is the same as for oxygen-bearing coppers.

Copper-Zinc Alloys (Brasses)

Copper-zinc alloys are commercially produced with varying percentages of copper and zinc with corresponding variations in the properties. Additions of a third or fourth metal are made occasionally to improve one or more of the mechanical properties. Brasses containing such additions are known as *alloy brasses* and the additions of manganese, tin, iron, silicon, nickel, lead and aluminum, either singly or collectively, rarely exceed 4.0%,

To simplify the discussion of brasses they will be divided into three classifications: Low brasses (80% Cu min.), high brasses (less than 80% Cu) and alloy brasses. The welding characteristics for all alloys in any one classification are quite similar. However, the resistance welding characteristics of the alloy brasses vary since addition of an alloying element generally reduces both electrical and thermal conductivities.

Low Brasses. (Cu 80 to 95%; Zn 5 to 20%).—These brasses have mechanical properties from medium to moderately high depending upon the specific composition. As the zinc content increases the tensile strength and hardness as well as the ductility increase; there is also a color change from red through gold to the green yellows with a progressive decrease in electrical and thermal conductivities (see Table 2). These are all single-phase alloys having a copper content of 80% or more. These low brasses possess hot-working properties comparable to those of copper, being plastic through a narrower temperature range (1350 to 1650°F). With increasing zinc content the hot-working properties decrease. *Red brass* (85% Cu, 15% Zn) shows a tendency for hot-shortness in the temperature range of 900 to 950°F. The lead content must be maintained at less than 0.01% so that these brasses can be hot forged, hot rolled or otherwise hot worked without any difficulty.

These low brasses are extremely ductile and malleable at room temperature and can be cold worked by any of the commercial methods such as deep drawing, spinning, stamping, forming, cold rolling, cold

Table 2—Wrought

Common Alloy Name →	Red Brass	Silicon Brass	Silicon Brass	High Brass
Nominal Composition, % →	85 Copper, 15 Zinc	77 Copper, 1.0 Si, 22 Zinc	70 Copper 0.5 Si, 29.5 Zinc	65 Copper, 35 Zinc
Chemical composition, %				
Copper	83.0–86.0	77.0–79.0	68.5–71.5	63.0–67.5
Silicon	....	0.75–1.25	0.3–0.6	....
Tin	....	....	....	....
Manganese	....	....	....	....
Iron	0.05 max.	0.1 max.	0.1 max.	0.05 max.
Lead	0.05 max.	0.05 max.	0.05 max.	0.10 max.
Other impurities	....	....	....	....
Zinc	Remainder	Remainder	Remainder	Remainder
Melting range, °F.				
Solidus	1810	1780	1680	1660
Liquidus	1880	1815	1750	1710
Electrical conductivity, % IACS at 68°F. (volume)	37	13	19	27
Thermal conductivity, Btu./ft.²/ft./°F./hr.	92	39	48	69
Specific heat, Btu./lb./°F. at 68°F.	0.09	0.09	0.09	0.09
Thermal expansion per °F., 68–572°F.	10.4×10^{-6}	10.3×10^{-6}	11.0×10^{-6}	11.3×10^{-6}
Forms available (indicated by (X) or applicable AST-M spec.)				
Plate, sheet, and strip	B36, Alloy 3	X	X	B36, Alloy 8
Rods, bars and shapes	B134, Alloy 3	....	....	B134, Alloy 7
Tube	B135, Alloy 1; B111	....	....	....
Pipe	B43[a]	....	....	....
Wire	B134, Alloy 3	....	....	B134, Alloy 7
Mechanical Properties				
Annealed:				
Tensile strength, psi.	37,000–44,000	53,000–72,000	53,000–62,000	46,000–57,000
0.5% yield strength, psi.	11,000–20,000	14,000–38,000	15,000–23,000	14,000–26,000
Elongation in 2 in., %	40–48	43–72	41–62	48–70
Hard:				
Tensile strength, psi.	63,000–73,000	87,000–110,000	84,000–96,000	68,000–84,000
0.5% yield strength, psi.	55,000–59,000	69,000–72,000	64,000–66,000	58,000–60,000
Elongation in 2 in., %	3–5	3.5–8	5–8	5–10

[a] ASME specification with the prefix SB identical with this ASTM specification.

heading, flaring and upsetting. Cold work will increase the tensile strength, yield strength and hardness, the amount of increase depending on the amount of cold work and the copper content of the specific alloy. After cold working, these brasses can be heat-treated (annealed) at temperatures ranging from 700 to 1400°F., to reduce their hardness and render them malleable and ductile again. Upon sudden exposure to elevated temperatures, these brasses when in a stressed condition are susceptible to cracking (fire-cracking). To avoid such failure, the stressed material should be brought up to temperature gradually. These brasses in general have the same corrosion resistance as copper except that they may have less resistance than copper to substances commonly called active chemical reagents. On the other hand, these brasses are more resistant than copper to the attack of sulfides, such resistance increasing with increasing zinc content. The 85% Cu, 15% Zn alloy (rich low or red brass) is better in its resistance to the corrosion of sea water than copper itself.

High Brasses (Cu 55 to 80%; Zn 20 to 45%).—The mechanical properties of these brasses are moderately high to quite high depending upon the composition. Such brasses, having a copper content from 80 to 64%, show a single phase (alpha brass). The tensile strength and hardness as well as ductility increase with an increase in zinc content in the same manner as for the low brasses. Brasses with copper content from 64 to 55% show two phases (alpha and beta brass) and their tensile strength and hardness increase with increasing zinc content; the ductility, however, decreases. These properties are affected by the ratio of the beta phase to the alpha phase. Alloys of the lowest copper content, because of the greater percentage of beta-phase brass are the strongest but least ductile. Both electrical and thermal conductivities de-

Copper-Zinc Alloys (Brasses)

Manganese Brass	Muntz Metal	Naval Brass	Manganese Bronze
66 Copper, 1 Manganese, 33 Zinc	60 Copper, 40 Zinc	60 Copper, 39¼ Zinc, ¾ Tin	58.5 Copper, 1 Iron, 1 Tin, 0.3 Manganese, 39.2 Zinc
64.5–67.5	58–61	59–61	51.0–60.0
....	....	....	....
....	0.25 max.	0.50–1.0	0.50–1.50
0.25–1.50	....	....	0.50 max.
0.06 max.	0.15 max.	0.10 max.	0.80–2.0
0.07 max.	....	0.20 max.	0.20 max.
0.10 max.	0.10 max.	Al 0.25 max.	....
Remainder	Remainder	Remainder	Remainder
1660	1650	1630	1590
1710	1660	1650	1630
20	28	26	24
....	70	67	61
0.09	0.09	0.09	0.09
11.3 × 10^{-6}	11.6 × 10^{-6}	11.8 × 10^{-6}	11.8 × 10^{-6}
X	B171[a]	B171[a]	X
....	X	B21	B124, Alloy 4; B138, Type A
....	X	X	....
....	....	....	....
....	....	....	....
Substantially same as high brass	50,000–55,000	50,000–60,000	55,000 min.
Substantially same as high brass	20,000–23,000	20,000–28,000	55,000 min.
Substantially same as high brass	35 min.	35 min.	25
	47–54	35–40	
Substantially same as high brass	78,000–88,000	88,000–96,000	68,000–80,000
Substantially same as high brass	61,000–62,000	67,000–70,000	45,000–50,000
Substantially same as high brass	7–12	3.5–5.5	10–20

crease as the zinc content increases provided the alloy contains only the single alpha phase. If beta brass is present the electrical and thermal conductivities increase slightly over the lower copper alpha brasses. The lower copper alpha brasses are relatively poor for hot working. Utmost care must be taken to keep the lead content to a trace in order to hot roll or hot forge these brasses within a temperature range of 1050 to 1550°F. The alpha-beta brasses are much easier to hot work, the ease of hot working increasing as the copper content decreases within the temperature range of 1200 to 1400°F. Lead content is not so critical and it is possible to hot roll alpha-beta brasses containing up to 1% lead by any process. The low copper alpha brasses work-harden less rapidly than those of higher copper content. Because of this, these brasses are used where successive drawing operations without intermediate annealing are involved. The alpha-beta brasses are difficult to cold work, this difficulty increasing with decreasing copper content. This is caused by the presence of the beta phase. Brasses containing 60 to 62% copper can be lightly cold worked because of the small percentage of the beta phase. Like the low brasses, these high brasses can be softened after cold-working operations by annealing within the temperature range of 700 to 1400°F. depending upon the properties desired. The alpha-beta brasses if quenched from the annealing temperatures, show a slightly higher hardness because of the formation of a greater amount of beta-phase brass than would be produced by air or furnace cooling. These brasses also show a tendency similar to the low brasses for fire-cracking if not properly handled during annealing or when heated. High brasses in general are similar to low brasses from the standpoint of corrosion resistance. When exposed to certain media they frequently fail in a manner termed *dezincification*, such failure being

characterized by spongy areas of copper in the form of layers or *plugs*. Under certain conditions the high brasses may also fail by *season cracking* or stress-corrosion cracking. Such failure is enhanced by the presence of internal stress or stress gradients produced by cold-working operations followed by exposure to corrosive atmospheres. The tendency of a cold-worked part to season-cracking may be minimized by annealing at a temperature of 500 to 700°F., which is below the recrystallization temperature (relief annealing).

Alloy Brasses.— In general, alloying additions in brasses are not sufficiently large to affect the general mechanical properties of the brasses. In some instances however, additions of tin, manganese and iron are made in sufficient quantities to secure a marked effect on the tensile strength, ductility and hardness. Lead is commonly added in amounts up to 4% to improve the machinability of brass but this has practically no effect on the tensile strength and hardness of brasses. Ductility and shear strength, however, particularly of cold-worked materials, are lowered by the addition of lead. Addition of a third metal other than lead in the small percentages normally used does not affect the cold-working properties of brass to any extent and may slightly improve the hot-working properties. All of the alloy brasses behave in a manner similar to the straight brasses with regard to annealing; lead additions increase the possibility of fire-cracking of materials stressed and subject to heat. The addition of small amounts of a third metal, particularly tin, improves the general corrosion resistance of the alloy brasses. Additions of small amounts of arsenic, phosphorus or antimony tend to inhibit the dezincification of the alpha brasses. The addition of aluminum aids in combating impingement-type corrosion and also increases the general corrosion resistance; lead has no effect on the corrosion resistance of alloy brasses.

Copper-Silicon Alloys (Silicon Bronze)

Copper-silicon alloys containing $1^1/_2$ to $3^1/_4$% silicon and $1^1/_4$% or less of zinc, tin, manganese or iron, have become important industrial materials because of their high strength, excellent corrosion resistance and ease of welding. The presence of a third metal has little effect on the general mechanical properties of silicon bronze. The addition of iron may cause an increase in tensile strength and hardness due to the formation of iron silicides. The addition of zinc or tin improves the fluidity of the molten bronze which tends to improve the quality of castings and weld metal deposited by oxy-acetylene welding. The addition of silicon to copper increases the tensile strength and hardness of the material. The ductility of silicon bronze is decreased with increasing additions of silicon up to about 1% and is then increased to a maximum value for 4% silicon. Toughness and shear strength increase with increasing silicon up to $3^1/_2$%. The electrical and thermal conductivities decrease as the silicon content increases (see Table 3). Silicon bronzes are very suitable for hot working and can be readily rolled, forged and extruded. Alloy A shown in Table 3, has a tendency toward cracking (hot-shortness) at temperatures above 600°F. Lead must be controlled in these materials to not more than a trace to avoid cracking in hot forging or hot rolling. The high silicon alloy work-hardens much more rapidly than the other alloys containing less silicon and because of this, high tensile strength and hardness can be obtained with the high silicon alloys. The lower silicon alloys possess more malleability and are used where good cold-working properties are necessary. All of the alloys shown in Table 3 can be softened after cold working by annealing within the temperature range 900 to 1400°F. When annealed in oxidizing atmospheres the scale formed on these alloys is very refractory and difficult to remove by ordinary cleaning methods. When cleaned in 10% solution (by volume) of sulfuric acid a red oxide surface is obtained which is termed a *plain pickle finish*. When this finish is immersed in a sodium bichromate solution containing 10% sulfuric acid by volume and $^3/_4$ lb. sodium bichromate per gallon of solution, a bright, oxide-free surface is obtained; this is termed a *specially cleaned finish*. If no cleaning is done the finish is termed *left black*. The silicon bronzes are subject to fire-cracking and susceptibility increases with increasing silicon content. In general the corrosion resistance of the copper-silicon alloys is equal to or better than that of copper. Like copper, these alloys are not suitable for use in resisting corrosion from turbulent or flowing sea

Table 3—Wrought Copper-Silicon Alloys (Silicon Bronze)

Type →	A (3%)	C (2½%)	B (1½%)
Chemical composition, %			
Major components:			
Silicon	2.75–3.50	2.00–3.00	0.75–2.00
Copper, min.	94.80	91.00	96.00
Optional elements[a]:			
Manganese, max.	1.50	1.25	0.75
Zinc, max.	1.50	4.50	1.50
Iron, max.	1.60	0.80	0.80
Tin, max.	0.75		1.60
Nickel, max.	0.60	0.60	
Lead, max.	0.05	0.05	0.05
Sum of above elements	99.50	99.50	99.50
Melting range, °F.			
Solidus	1780	1805	1890
Liquidus	1860	1905	1940
Electrical conductivity, % IACS at 68°F. (Volume)	7	....	12
Thermal conductivity, Btu/ft.²/ft./°F./hr. at 68°F.	21	....	33
Specific heat, Btu./lb./°F. at 68°F.	0.09	....	0.09
Thermal expansion per °F., 68 to 572°F.	10×10^{-6}	....	9.9×10^{-6}
Forms available (indicated by (X) or applicable ASTM Spec.)			
Plate, sheet, strip	B96[b]; B97, Alloys 1–7; B100, Type 8; B124, Alloys 7	B96[b]; B97, Alloys 21–24	B97, Alloys 11–17; B124, Alloy 8
Rods, bars, shapes	B98[b], Alloys 2–7	B98[b], Alloys 22–24	B98[b], Alloys 11–17
Wire	B99, Alloys 2–7	B99, Alloys 22–24	B99, Alloys 11–17
Tube	X	....	....
Mechanical properties			
Hot rolled:			
Tensile strength, psi.	55,000–72,000		....
Annealed:			
Tensile strength, psi.	50,000–67,000		28,000–50,000
0.5% yield strength, psi. min.	18,000		12,000
Elongation in 2 in., %	40		35
Cold rolled (hard):			
Tensile strength, psi	87,000–97,000		60,000–70,000
0.5% yield strength, psi, min.	50,000		35,000
Elongation in 2 in., %	8–22		8–12

[a] One or more of the following elements may be present within limits prescribed in specifications.
[b] ASME Specification with the prefix SB identical with this ASTM specification.

water. The silicon bronzes are subject to stress corrosion failures, particularly Alloy A; severely worked copper-silicon alloys should be stress relieved to minimize this hazard.

Copper-Tin Alloys (Phosphor Bronze)

Alloys of copper and tin are properly termed *tin bronze*. Because 0.03 to 0.04% phosphorus is generally added as a deoxidizing agent in the casting of these alloys, the tin bronzes have come to be known commercially as *phosphor bronze*. Phosphor bronzes have moderately high to very high tensile strength depending upon the amount of tin; commercially available alloys contain from 1.5 to 10% tin. When in the completely homogenized condition, they are single-phase alloys and have a structure similar to alpha brass. With tin content of more than 5% the alloys are very difficult to cast without dendritic segregations. In the wrought form the alloys are tough and hard and have high fatigue resistance, particularly in the cold-worked condition. Electrical and thermal conductivities are quite low for the phosphor bronzes of low tin content and very low for the phosphor bronzes of high tin content (see Table 4). Phosphor bronzes have a very narrow plastic range and must be hot worked at temperatures ranging between 1150 and 1225°F. Low tin alloys (under 4%) have the best hot-working properties. All of the phosphor bronzes have very good cold-working properties including high strength and hardness in the hard rolled tempers. Annealing after light cold-working operations is desirable. After cold working, these alloys can be rendered soft and malleable by annealing at temperatures between 900 and 1400°F. depending upon the properties desired. In a stressed condition the phosphor bronzes are subject to fire-cracking and care must be taken to avoid thermal shock by the sudden application of high heat. The corrosion resistance of these alloys is comparable to that of copper. For some services the copper-tin alloys are superior to copper, particularly against corrosion by

Table 4—Wrought Copper-Tin Alloys (Phosphor Bronze)

Type →	Grade A, 5%	Grade C, 8%	Grade D, 10%	Grade E, 1.25%
Chemical composition, %:				
Tin	3.50–5.80	7.0–9.0	9.00–11.0	1.0–1.50
Phosphorus	0.03–0.35	0.03–0.35	0.07–0.25	Trace
Zinc, max.	0.30	0.20	0.20	....
Copper:				
Commercial, min.	94	90.50	88.50	98.50
Specification	Remainder	Remainder	Remainder	....
Manganese, max.	1.25% for rod over 1.25 in. diameter			....
Iron, max.	0.10 (1.25% for rod over 1.25 in. diameter)			....
Lead, max.	0.05	0.05	0.05	....
Antimony, max.	0.01 in plate, sheet and strip			....
Sum of elements for flat, rod or wire	99.50	99.50	99.50	....
Melting range, °F.:				
Solidus	1750	1620	1550	1900
Liquidus	1920	1880	1830	1970
Electrical conductivity (volume), % IACS at 68°F.	18	13	11	48
Thermal conductivity, Btu./ft.²/ft./°F./hr. at 68°F.	46	36	29	119
Thermal expansion per °F., 68 to 572°F.	9.5×10^{-6}	10.1×10^{-6}	10.2×10^{-6}	9.9×10^{-6}
Specific heat at 68°F., Btu./lb./°F.	0.09	0.09	0.09	0.09
Forms available (indicated by (X) or applicable ASTM spec.):				
Plate, sheet and strip	B103, Grade A	B103, Grade C	B103, Grade D	X
Rods, bars and shapes	B139, Grade A	B139, Grade C	B139, Grade D	....
Wire	B159, Grade A	B139, Grade C	B159, Grade D	(See B105, Grade 40)
Tube	X	....	....	....
Mechanical properties:				
Annealed:				
Tensile strength, psi.	40,000–61,000	51,000–68,000	54,000–73,000	40,000
0.5% yield strength, psi.	16,000–42,100	20,200–46,600	21,200–40,800	14,000
Elongation in 2 in., %	41–60	50–71	57–65	48
Hard:				
Tensile strength, psi.	72,000–92,000	85,000–104,000	94,000–109,000	65,000
0.5% yield strength, psi.	60,700–72,250	72,300–74,600	71,000–77,100	50,000
Elongation in 2 in., %	5–7.5	5–12	10–11	8

sea water and acid reagents. In the stressed condition these materials are subject to stress corrosion and severely worked parts should be stress relieved before being put in service; this is particularly true with the high tin alloys.

Copper-Aluminum Alloys (Aluminum Bronze)

Copper-aluminum alloys are commercially high copper alloys containing 4 to 10% additions of aluminum and additions of nickel, iron, silicon and manganese in varying low percentages. The commercial alloys are of two types: alpha- or single-phase with up to 7.5% aluminum and alpha-beta or two-phase known as *duplex bronzes* with over 7.5% aluminum. The tensile strengths of alpha aluminum bronzes are equal to those of the high brasses. They are tough, moderately hard and have high ductility. The duplex alloys have a very high tensile strength but are lacking in ductility; they have very high hardness comparable to work-hardened copper-silicon alloys. Because of the high hardness of the duplex structure, the alloys have high wear resistance. Electrical and thermal conductivities are fairly low being comparable to those of the low silicon bronzes (see Table 5). The alpha-type aluminum bronzes have a reasonably wide plastic range and can be worked at temperatures between 1450 and 1650°F. The duplex bronzes have an even wider plastic range and are hot worked best in the temperature range of 1300 to 1650°F. Alpha aluminum bronzes are very satisfactory for cold working but since they work-harden rapidly, they are not generally used for severe drawing or stamping operations. The duplex bronzes on the other hand, have very poor cold-working properties and can only be cold worked slightly. Alpha aluminum bronzes are similar to alpha brasses and can be softened by annealing in the temperature range of 900 to 1400°F. depending upon the properties required. Annealing of the duplex bronzes has little effect on the hardness because of the existence of the alpha-beta structure. Since duplex bronzes cannot be cold worked, annealing operations are used

Table 5—Wrought Copper-Aluminum Alloys (Aluminum Bronze)

Type →	5%	8%	10%	10%
Nominal Composition, % →	95 Copper, 5 Aluminum	92 Copper, 8 Aluminum	90 Copper, 10 Aluminum	82.5 Copper, 10 Aluminum, 5 Nickel, 2.5 Iron
Chemical composition, %:				
Copper	92–96	90–93	80–93	Remainder
Aluminum	4.0–7.0	7.0–9.0	6.50–11.00	8.00–11.00
Nickel	....	....	1.00 max.	4.00–7.00
Iron, max.	0.50	0.50	4.00	1.50–3.50
Manganese	....	....	1.50	1.50–2.00
Silicon, max.	....	...	2.25	....
Tin, max.	....	....	0.60	
Zinc, max.	....	....	1.00	....
Tellurium, max.	....	....	0.65	....
Other elements, max.	0.50	0.50	0.50	0.50
Electrical conductivity (volume), % IACS at 68°F.	17.5	15.2	12.6	7.5
Thermal conductivity, Btu./ft.²/ft./°F./hr. at 68°F.	....	....	....	....
Melting range, °F.:				
Solidus	1920	1888	1890	1895
Liquidus	1940	1897	1905	1930
Thermal expansion per °F., 68 to 572°F.	10.0 × 10⁻⁶	10.0 × 10⁻⁶	10.3 × 10⁻⁶	10.3 × 10⁻⁶
Specific heat, Btu./lb./°F.	....	....	0.104	0.104
Forms available (indicated by (X) or applicable ASTM spec.)				
Sheet, plate and strip	B169, Alloy A	B169, Alloy C; C124, Alloy 11	....	B171
Rods, bars and shapes	B124, Alloy 10	B124, Alloy 11; B150, Type 1	B150, Type 1; B124, Alloy 11	B150, Type 11
Condenser tube	B111	....	....	..
Mechanical Properties:				
Annealed:				
Tensile strength, min. psi.	45,000	50,000	70,000–80,000	90,000
0.5% yield strength, min., psi.	17,000	20,000	42,000–50,000	36,000
Elongation in 2 in., min., %	40	30	20–15	10
Hard:				
Tensile strength, min., psi.	50,000–60,000	....	....	....
0.5% yield strength, min., psi.	20,000–24,000	22,000–27,000	....	....
Elongation in 2 in., min., %	30–25	25–20	....	....

to refine or change the grain structure after hot working. The mechanical properties of duplex bronzes can be improved by quenching in water from temperatures of 1500 to 1600°F. and re-annealing between 700 and 1100°F. All of the aluminum bronzes resist scaling or oxidization at elevated temperatures to a high degree. This is due to the presence of aluminum and the resistance increases with increasing aluminum content. Aluminum bronzes possess a high resistance to mineral acid attack, such resistance increasing with increasing aluminum content. This resistance is due to the formation of aluminum oxide on the exposed surfaces. The oxide film is quite soluble in alkalies so that the alloys have low resistance to the attack of strong alkalies. Under certain corrosive conditions the alpha-beta aluminum bronzes are subject to a form of corrosion called *dealuminization*, which is analogous to dezincification in brass. All of the aluminum bronzes have excellent resistance against sea water, particularly turbulent sea water.

Copper-Nickel Alloys

Copper-nickel alloys are available commercially in three major alloys containing 10, 20 and 30% nickel (see Table 6). These alloys have moderately high to high tensile strength depending upon the nickel content. They are moderately hard, quite tough and fairly ductile; electrical and thermal conductivities are low. All of these alloys have good hot-working properties except that they are not considered suitable for hot forging because of poor flowing qualities. These alloys have excellent cold-working properties with a degree of malleability approaching that of copper. Since they do not work-harden rapidly, they can be used in severe drawing, stamping and spinning operations. Like the 70 Cu, 30 Zn brass, these alloys

Table 6—Wrought Copper-Nickel and Copper-Nickel-Zinc Alloys (Cupro-Nickel and Nickel Silver)

Type or Alloy Name →	Cupro Nickel, 20%	Cupro Nickel, 30%	Nickel Silver, 18% (B)
Nominal Composition, % →	80 Cu–20 Ni	70 Cu–30 Ni	55 Cu–18 Ni–27 Zn
Chemical composition, %:			
Copper	Remainder	Remainder	53.5–56.5
Nickel	19–23	29–33	16.5–19.5
Zinc, max.	1.0	1.0	Remainder
Tin, max.	1.0	1.5	....
Manganese, max.	1.0	1.0	0.50
Iron, max.	0.6	1.0	0.05
Lead, max.	0.05	0.05	0.05
Melting range, °F.:			
Solidus	2070	2140	....
Liquidus	2190	2260	1930
Electrical conductivity, % IACS at 68°F. (volume)	6.5	4.6	5.5
Thermal conductivity at 68°F., Btu./ft.²/ft./°F./hr.	22	16.9	16.9
Thermal expansion per °F., 68–572°F.	8.95×10^{-6}	9.0×10^{-6}	9.25×10^{-6}
Specific heat at 68°F., Btu./lb./°F.	0.09	0.09	0.09
Forms available (indicated by (X) or applicable ASTM Spec.)			
Sheet, strip and plate	B122, Alloy 6	B122, Alloy 5, B171, B171[a]	B122, Alloy 4
Rods, bars and shapes	X	X	B151, Alloy B
Tube	B111,[a] Type A	B111[a]	....
Wire	....	X	B206, Alloy B
Mechanical Properties			
Annealed:			
Tensile strength, psi.	49,000–53,000	50,000	60,000
0.5% yield strength, psi.	13,000–23,000	20,000	27,000
Elongation in 2 in., %	35	35	40
Hard:			
Tensile strength, psi.	67,000–79,000	75,000–88,000	92,000–197,000
0.5% yield strength, psi.	72,000–74,000	76,000–78,000	85,000
Elongation in 2 in., %	4	4	3

[a] ASME specification with the prefix SB identical with this ASTM specification.

can be softened by annealing within a temperature range of 1200 to 1600°F., depending upon the properties desired. The presence of nickel in these alloys makes them very satisfactory for corrosion resistance. They are particularly resistant to the erosive and corrosive attack of high velocity sea water and this resistance improves with increasing nickel content. These alloys are very resistant to stress corrosion and corrosion fatigue, these characteristics increasing with increasing nickel content.

Nickel Silver

Nickel is added to the copper-zinc alloys primarily to lighten their color and the resulting alloys are called *nickel silver*. These alloys are of two general types: an alloy containing 65% or more of copper and nickel combined and consisting of a single phase and an alloy containing 55 to 60% of copper and nickel combined and consisting of two phases. Table 6 gives the properties of the latter alloy; the former alloy is not generally used for welding and is not covered in this chapter. The tensile strength of nickel silver is quite high. The hardness of these materials varies, the two-phase alloys having a high hardness. Electrical and thermal conductivities of the alloys are quite low. The single-phase, nickel-silver alloys are very seldom processed by hot working. Because of its plasticity over a wide temperature range the two-phase nickel silver may be hot worked by any of the commercial processes. The addition of lead to improve machining, however, makes this alloy unsuited for hot rolling and forging although the leaded alloys can be extruded hot without difficulty. The single-phase nickel silvers are very satisfactory for deep drawing, stamping and spinning; the two-phase alloys are difficult to cold work and are not commonly processed by any of the cold-working methods. These alloys can be softened by annealing in a temperature range of 900 to 1300°F. depending upon the properties desired. The two-phase alloys are usually annealed after hot working to refine the structure. Although the general corrosion resistance of nickel silver is enhanced by the presence of nickel, the high zinc content of these alloys makes

Table 7—Wrought-Beryllium Copper

Nominal composition, % →	2 Beryllium, 97.75 Copper, 0.25 Cobalt (or 0.35 Nickel)			
Chemical composition, %:				
Beryllium	1.90–2.15			
Additive elements:				
Nickel or cobalt or both, min.	0.20			
Nickel or cobalt plus iron, max.	0.60			
Copper plus beryllium plus additive elements, min.	99.50			
Melting range, °F.:				
Solidus	1587			
Liquidus	1750			
Electrical conductivity (volume), % IACS at 68°F.	Solution treated, quenched (A) 17 A + precipitation hardening (AT) 21 Condition A 48.4 Condition AT 60.5			
Thermal conductivity at 68°F., Btu./ft.²/ft./°F./hr.				
Thermal expansion per °F.:				
68–212	9.2×10^{-6}			
212–392	9.55×10^{-6}			
392–572	10.55×10^{-6}			
Specific heat, 86–212°F., Btu./lb./°F.	0.1			
Forms available (indicated by (X) or applicable ASTM Spec.)				
Plate, sheet and strip	B194, B195			
Rod, bars and shapes	B196			
Tube	X			
Wire	B197			
Mechanical Properties				
Mill Treatment	Cold rolled			
	Solution treated, quenched		Rolled hard	
Condition	As supplied, A	Precipitation Hardened,[a] AT	As supplied, H	Precipitation Hardened, HT
Tensile strength, psi.	80,000 max.	150,000 min.	95,000 min.	180,000 min.
Elongation in 2 in., min., %	35	5	2 0	1.0
Rockwell hardness	80B max	32C min.	93B min.	39C min.

[a] For purposes of acceptance tests, heat treatment at 600 ± 5°F. is specified for the following times: solution treated (A), 3 hours; hard (H), 2 hours.

them subject to dezincification under certain conditions. These alloys are also subject to stress corrosion if highly stressed and should therefore be stress relieved before being placed in service.

Copper-Beryllium Alloys

Copper-beryllium alloys usually contain approximately 1¹/₂ to 2¹/₂% beryllium with slight additions of iron, nickel and silver. These alloys have only moderate tensile strength in the cold-rolled, not age-hardened, condition. When age-hardened they have extremely high tensile strength and hardness. Similarly, electrical and thermal conductivities are lower in the non-aged condition than in the aged condition. These alloys are quite ductile when softened but lose their ductility if cold rolled or age-hardened. These alloys are characterized by high endurance limits under fatigue stress. Age-hardening of these alloys is accomplished by heating for two hours at 525 to 600°F. Copper-beryllium alloys are generally good for hot working but care must be taken to insure complete solution of copper-beryllium compounds. This is done by soaking them for prolonged periods prior to hot working. Copper-beryllium alloys are suitable for cold working provided they have not been age-hardened prior to cold working. These alloys do not work-harden too rapidly and can be drawn, stamped or spun. The cold-worked or age-hardened alloys can be rendered soft and malleable by annealing for two to three hours at 1450 to 1500°F., followed by water quenching. These alloys have a corrosion resistance comparable to copper or copper-silicon alloys (see Table 7).

HOW TO WELD

Carbon-Arc Welding

Copper.—Oxygen-bearing copper can be joined by carbon-arc welding with varying degrees of success. Because of the presence of copper-cuprous oxide eutectic, embrittlement is encountered to some extent, due to the high reducing atmosphere surrounding the weld area. The degree of embrittlement depends on the length of time the superheated copper is in contact with the reducing gases in the welding area. High fluid welding rods, such as Grade C or Grade D phos-

phor bronze, give best results because of the higher lineal speeds of welding attainable with these rods. It is not practical to attempt the carbon-arc welding of this copper in thicknesses over 3/8 inch. Low-tin phosphor bronze (Grade E) can also be used for material up to 1/4-in. thick with Grade C and Grade D rods. The low-tin rods permit the weld to be cold worked and are preferred for thicknesses up to 1/4 in. if cold working is to be done after welding. No flux is required with these welding rods.

Copper-silicon welding rods should not be used for oxygen-bearing copper. The lower welding speeds required with these rods permit the reduction of more copper oxide causing embrittlement.

Material 3/16- to 3/8-in. thick should have a 45-deg. single-vee groove and a root opening of 3/32 to 3/16 in. should be used, the larger root opening being for the thicker material. A backing should always be used to eliminate burning through. Graphitic-type carbon electrodes, sharpened to a long tapered point, should be used (see Chapter 9). The size of electrode should be at least equal to the size of welding rod, preferably larger. Multiple-pass welding is not generally recommended.

Oxygen-free coppers are more easily welded with uniform results because of the absence of the copper-cuprous oxide eutectic in the copper. Lineal speeds of welding will only affect the density of the weld and will be determined by the welding heat used. Copper-silicon welding rods have proved most successful because of their ability to withstand the high heats of welding and ease of control of weld metal. Multiple-pass welding can be done, which permits the welding of all thicknesses of copper. Flux designed for use with copper-silicon alloy welding rods should be used and applied as recommended under copper-silicon alloy welding (see page 749). Material 3/16- to 3/4-in. thick should have a 45-deg. single-vee groove; a 45-deg. double-vee should be used for thicker material. Root openings of 3/32 to 3/16 in. should be used depending on the thickness of the base metal. All welding should be done in a downhand position, and a copper backing used. If the backing is to be removed after welding, the thickness should not be less than 3/8 inch. It is recommended that a groove approximately 1/4-in. wide and 1/32-in. deep, be machined lengthwise in the bar to aid in obtaining proper penetration. A backing, approximately 1/8-in. thick, may be used and left as a reinforcement on the underside of the weld.

Phosphor bronze, Grade C or D, welding rods are used quite successfully for carbon-arc welding oxygen-free coppers. Multiple-pass welding is not recommended and the thickness of copper should be limited to 3/8 inch. The ductility of the weld metal is not sufficient to allow much cold working or forming after welding. The high fluidity of the weld metal on heavier gages of copper has a tendency to cause cold laps. To minimize this, the work should be tilted to an angle of 7 to 15 deg. to permit welding slightly uphill to prevent the weld metal from flowing ahead of the arc. No flux is required; joint preparation and root openings are the same as for copper-silicon welding rods.

Copper-Zinc Alloys (Brasses).—Carbon-arc welding is suitable for welding the low brasses using a copper-silicon welding rod containing 3% silicon. With proper manipulation of the arc, very little fuming will occur since a minimum amount of the base metal is disturbed. The fuming that may occur is caused by the evolution of zinc from the base metal, which combines with oxygen of the atmosphere to form zinc oxide (white fumes). Phosphor bronze welding rods containing 8 and 10% tin can be used for single-pass welds but copper-silicon welding rods should be used for multiple-pass welds.

For thicknesses under 3/16 in. a square groove may be used, with a grooved backing. For thicknesses between 3/16 and 1/2 in., a 45-deg. single-vee groove should be used; for 1/2 to 3/4 in. a 37 1/2-deg. groove angle should be used. All thicknesses should be welded by multiple-pass welds and suitable flux, in the form of a thin alcoholic paste, applied to the work and the welding rods.

For carbon-arc welding the high brasses either a low fuming bronze or a copper-silicon welding rod containing 3% silicon should be used. The copper-silicon welding rod is preferred because of its greater ease of handling during welding and the greater ductility of the resulting weld. The welding of the high brasses causes a considerable evolution of zinc fumes. These fumes (zinc oxides) must be re-

moved and this is best done with the use of exhaust fans and flexible hose leads.

Preheating of the base metal, not in excess of 400°F., is essential to obtain proper fusion and sound weld metal. All metal thicker than $^{1}/_{8}$ in. should be beveled to a 45-deg. groove angle to minimize disturbance of the base metal. Multiple-pass welding is recommended for thicknesses $^{3}/_{16}$ in. and heavier. Particular care should be taken to chip out all crater cracks that occur at all stops in the welding, particularly if low-fuming bronze welding rods are used. Flux should be used in the same manner as recommended for copper-silicon alloy welding, i.e., thin paste with alcohol painted on the cold work before preheating and dry flux sprinkled on lightly after the work is hot. The proper flux should be used in each instance as different fluxes are required for the copper-silicon and the low-fuming bronze welding rods.

Copper-Silicon Alloys (Silicon Bronze).—Silicon bronzes may be welded by carbon-arc welding using welding rods of approximately the same composition. The ease of welding is due to the low thermal conductivity, the lack of interference of oxides or compounds formed, and the flowing properties and density of the weld metal. Phosphor bronze (Grade C or D) welding rods are suitable for thicknesses up to $^{1}/_{4}$ in. but are not commonly used because of their greater fluidity.

Graphite electrodes are superior to ordinary carbon electrodes. For best results, the electrodes should be sharpened to a long tapered pencil point. When the point becomes blunt, the electrode should be changed. The size of electrode should never be less than the size of the welding rod and preferably slightly larger.

Cleanliness is of prime importance for uniformity in the quality of the weld. Grease, oil, paint and dirt should be thoroughly removed. Heavy black oxide scale should also be removed either by pickling or grinding the surfaces adjacent to the weld area prior to welding.

Suitable flux must be used to insure uniform results. This flux is best applied to the cold work by brushing on a thin paste made with methyl alcohol along the edges to be joined. When the work is hot, the dry flux should be sprinkled on the work prior to welding.

Excessive heat will cause hot-short cracks in the weld metal. Crater cracks at the ends of a weld are due to the shrinkage of the metal induced by higher heats when the arc is broken.

All welding should be done with as few stops and starts as possible to minimize crater cracks. When such stops do occur, it is advisable on the next start to strike the arc about 1 in. back from the last stop. Because of the hot-short characteristics of these alloys, all welding layers after the first in multiple-pass welding should be started at a point about 2 to 4 in. from the end of the joint. After completion of this layer, the unwelded portion should then be welded from the start of the layer to the end of the joint.

It is advisable to bevel all thickness $^{3}/_{16}$ in. and heavier using a $37^{1}/_{2}$- to 45-deg. angle of bevel. Single-vee groove butt joints are recommended for thicknesses $^{1}/_{16}$ to $^{3}/_{4}$ in. without backing. For thicknesses over $^{3}/_{4}$ in., double-vee groove butt joints are recommended. (Root opening should be from $^{1}/_{16}$ to $^{1}/_{8}$ in. depending on thickness of base metal.) Thicknesses $^{3}/_{32}$ in. and heavier should be welded using multiple passes. In laying down the first pass, a small welding rod with low heat should be used, and the rod size and current input increased for later passes. Slag should be removed from each layer by the use of a wire brush before starting the succeeding layer.

Copper-Aluminum Alloys (Aluminum Bronze).—Carbon-arc welding is used rather extensively for joining the aluminum bronzes, especially where an exceptionally dense deposit is required and the higher heat developed in welding by this process is permissible.

Covered filler metal of Classifications ECuA1-A, B, C, D and E (see Chapter 38) are recommended for use with this process instead of bare rods because the very refractory aluminum oxides formed during welding must be thoroughly fluxed in order to obtain a satisfactory deposit. Covered electrodes are available in 36-in. lengths for this purpose.

The size of carbon electrode to be selected depends upon the welding rod diameter and the welding current required for the specific application. In general, the current ranges found satisfactory for the average high graphite electrode used for this purpose are as follows:

Carbon Electrode, Diam., In.	Welding Rod, Diam., In.	Current, Amp.
3/16	3/32, 1/8, 5/32	60–80
1/4	5/32, 3/16	80–130
3/8	3/16, 1/4	130–250
1/2	1/4, 5/16	250–350
3/4	5/16, 3/8	350–500
1	3/8, 1/2	500–700

Carbon electrodes should be formed by grinding or filing the carbon rod to a conical taper 4 or 5 in. in length. Straight polarity (electrode negative, work positive), direct current should be used in welding.

Groove preparation can be determined by referring to Fig. 1. In carbon-arc welding it is permissible to use a 60-deg. single-vee groove for the heavier sections.

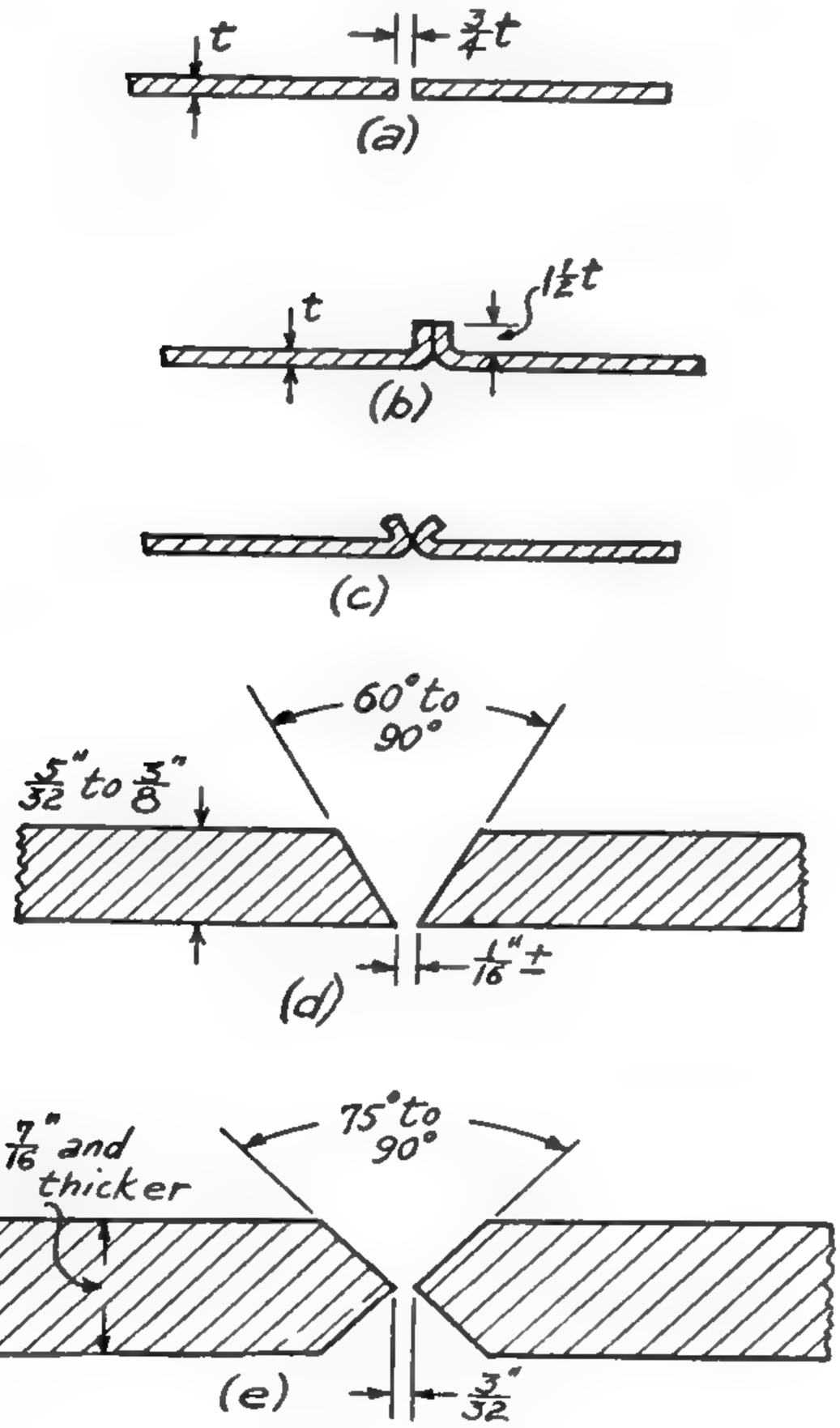


Fig. 1.—Edge Preparations for Welding Copper and Copper Alloys

A backing of matching plate is desirable.

For the low aluminum grades in heavy sections, a preheat and interpass temperature of 400°F. should be used. For the higher aluminum grades (Rockwell 90B and over), preheat temperatures should range from 700 to 800°F. to avoid cracking of the deposit.

In groove welding, the graphite electrode is directed back on the deposited weld metal at an angle of approximately 15 deg. to the horizontal. The arc length should be about equal to the diameter of the welding rod. The electrode is pointed back toward the completed weld for two definite reasons: (1) to control the flow of the slag formed in welding with covered filler metal so the slag will form over the deposited metal rather than run ahead of the bead; (2) the deposited weld metal flow can be directed more easily filling in undercut formed at the side walls.

The intense heat of the carbon-arc can be evenly distributed if the carbon electrode is manipulated with a rapid weaving motion. The width of this weave will be determined by the type of weld and the dimensions of the joint or work which is being welded. All slag should be thoroughly cleaned between layers. All welding should be done in the flat position. No postheat treatment is required for the low aluminum grades. For the high aluminum grades an anneal at 1150°F. is required followed by rapid cooling with a blast of air.

Copper-Beryllium Alloys (Beryllium Copper).—The carbon-arc welding process is used in joining beryllium copper and surfacing areas with beryllium copper deposits using a coated welding rod. Like the refractory oxides formed in welding the aluminum bronzes, the very refractory beryllium oxides formed during welding must be thoroughly fluxed in order to obtain sound, slag-free deposits. Beryllium copper electrodes are available in either short lengths or in 36-in. lengths. Electrodes having nickel as a secondary alloy are preferred to those having cobalt since the deposited weld metal obtained from them have maximum mechanical properties in the heat-treated condition.

Base metal preparation and welding technique are the same as those described for carbon-arc welding of the aluminum bronzes. Recommended preheat and interpass temperature is usually from 600 to 700°F.

In service, beryllium copper is usually heat treated to develop maximum mechanical properties. Therefore, heat treatment is recommended after welding, con-

sisting of heating the part to 1450°F., holding at this temperature for one hour per inch of thickness, and water quenching and drawing at 600°F.

Dissimilar Metals.—The joining of any of the various copper-alloy base metals to each other or to steel can successfully be done by carbon-arc welding. Specific comments concerning the welding of the various alloys themselves should be taken into consideration before starting the job. Copper-silicon welding rods will give the best and most uniform results except when oxygen-bearing copper is one of the base metals. Phosphor bronze, Grades C or D, welding rods can also be used but are subject to the same limitations as when welding similar base metals.

Copper-silicon welding rods are usually used for joints between copper and steel sections. For best results, no melting of the steel must occur since high porosity and brittleness will result. To minimize steel disturbances, an oversized welding rod and a concentration of heat on the welding rod and copper-alloy base metal are recommended. Flux should be used as previously specified under copper-silicon alloy welding.

Shielded Metal-Arc Welding

General.—Coated electrodes of composition similar to the base metals covered in this chapter are available for use in shielded metal-arc welding of copper and the copper alloys with the exception of the copper-zinc alloys (brasses). The brasses can be welded with either phosphor bronze, aluminum bronze or silicon bronze electrodes depending on the base metal composition and service requirements. Bare electrodes can also be used to weld copper, the copper-tin and copper-silicon alloys. (Also see Chapter 10 for further information on shielded metal-arc welding.)

Most copper and copper-alloy covered electrodes are designed to operate with d.c. reverse (positive) polarity, although some grades are also available for use with alternating current. Techniques for metal-arc welding of copper and the copper alloys vary slightly from those used in steel welding because the alloys have:

1. Higher thermal conductivity.
2. Higher electrical conductivity.
3. Higher coefficients of thermal expansion.
4. Lower melting points and greater fluidity of the molten metal at arc-welding temperatures.

As compared with steel welding it is necessary, generally, in metal-arc welding of copper and copper alloys to:

1. Allow greater root openings.
2. Use larger groove angles.
3. Tack weld more frequently.
4. Use higher preheat and interpass temperatures.
5. Use higher current for size of electrode and plate thickness.

Recommended joint designs are shown in Fig. 1. Tight joints are to be avoided in light sections. Wide grooves are necessary in heavy sections to avoid excessive undercutting, slag inclusions and porosity.

Generally, backings of the same composition as the base metal are used, although copper and carbon strips can be used satisfactorily with most of the alloys. A grooved backing strip is often used resulting in the formation of a small bead on the under side of the joint.

Although copper and copper-alloy electrode deposits flow smoothly in iron-base metals, most deposits flow rather sluggishly in matching plate compositions. Therefore, higher preheat and interpass temperatures are required, especially for joining heavy sections (see Table 8). A good general rule to follow in preheating copper and copper alloys is to use 400°F. for bronze, with the exception of silicon bronze for which the temperature should not exceed 150°F.; 500 to 600°F. for brasses; 700°F. for beryllium-copper; and 800°F. for copper.

All-weld-metal values shown in Table 9 are as-welded with electrodes of similar composition except those given for the copper-zinc (brass) alloys. Low-strength brasses are usually welded with phosphor bronze electrodes and the higher strength brasses are joined with aluminum bronze electrodes.

Peening is often used to reduce stresses in the joints and to some extent improve the mechanical properties by refining the grain of the deposit. Flat-nosed tools with numerous moderate blows should be used; if blows are too vigorous, localized failure may occur.

Copper.—Electrolytic, tough pitch copper is not recommended for joining by means of welding if strength joints are re-

quired, because the dispersed cuprous oxides present in the base metal cause embrittlement of the joint at the fusion zone, resulting in loss of strength to approximately one third that of the base metal.

Copper may be joined by soft soldering or brazing. If strength joints are not essential, welding can be readily accomplished with electrodes ECu, ECuSn-A, ECuSi and bare rods of similar compositions as described under deoxidized copper.

In the shielded metal-arc welding of copper, deoxidized copper electrodes, ECu, and bare rods of similar composition must be used where the metal is required to have high thermal or electrical conductivity or corrosion-resisting characteristics comparable to the base metal. Where service requirements will allow, phosphor bronze (ECuSn-A) and silicon bronze (ECuSi) electrodes may be used because the deposits flow better at lower preheat and interpass temperatures. In metal-arc welding, a grooved backing strip of copper should be used with a wide groove. The joints may be restrained moderately by clamping. Tight clamping will cause the deposits to crack. Downhand welding only is recommended.

Preheat and interpass temperatures of 800 to 1000°F. must be used and maintained, especially on heavy sections, due to the high thermal conductivity of copper. The largest diameter electrode possible should be selected and high current is required to flow the weld metal into the side walls thereby minimizing undercutting and the resultant slag inclusions. Either weave or string beads can be used depending upon the width of the groove. Usually, no postheat treatment is required.

Copper-Zinc Alloys (Brasses).—Both the high and low brasses are readily welded by the shielded metal-arc process with phosphor bronze (ECuSn-A) or aluminum bronze (ECuAl-A) electrodes depending upon the service requirements and the mechanical properties desired. The ECuAl-A electrode is used where high tensile strength, high fatigue strength and corrosion resistance are necessary. The ECuSn-A electrode is recommended for the lower zinc content alloys where tensile strength requirements are 40,000 p.s.i. maximum. Lead-bearing copper-zinc alloys are considered unweldable if a sound, porous-free deposit is required.

A backing strip of either matching plate

Table 8—Copper & Copper Alloy Electrode Selection & Preheat Chart[a]

Alloy →	Low Nickel Steel	Manganese Steel	Tool Steel	Stainless Steel	Cast Iron	Carbon Steel	Copper-Beryllium	Copper-Nickel	Copper Aluminum	Copper-Tin	Copper-Silicon	Copper-Zinc	Copper
Copper	3G	3G	3G	3G	3G	3G	3G	5, 3G	3, 2G	3, 2G	2G	3, 2G	1, 3, 2G
Copper-zinc	3, 4D	3, 4D	3, 4F	3, 4D	3, 4D	3, 4D	3, 4F	5, 4D	3, 4D	3, 2D	3, 2D	3, 2, 4D	
Copper-silicon	2, 3, 4A	2, 3, 4A	2, 3, 4F	2, 3, 4A	2, 3, 4C	2, 3, 4A	2, 4F	2, 5C	2, 4A	3, 2C	2A		
Copper-tin	3C	3C	3F	3C	3C	3C	3, 2F	3, 5C	3C	3C			
Copper-aluminum	4C	4C	4F	4C	4, 3D	4C	4F	4, 5C	4C				
Copper-nickel	5, 4A	5, 4A	5, 4F	5, 4A	5, 4C	5, 4A	4, 5F	5A					
Copper-beryllium	4, 3F	4, 3F	4, 3F	4, 3F	3, 4F	4, 3F	6F						
Carbon steel	4	4B	4F	4	3, 4C								
Cast iron	4, 3C	4, 3C	4, 3F	4, 3C	4, 3C								
Stainless steel	4B	4B	4F										
Tool steel	4F	4F	4F										
Manganese steel	4B	4B											

Electrode	Preheat and Interpass Temperature
1—ECu	A—150°F.
2—ECuSi	B—300°F.
3—ECuSn-A or ECuSn-C	C—400°F.
4—ECuAL-A	D—500°F.
5—ECuNi	F—700°F.
6—Beryllium	G—800°F.-1000°F.

[a] *How to Use This Chart:* Recommended electrode for welding like and dissimilar metals with bronze electrodes is coded by number. Electrodes are selected according to weldability except in those cases where mechanical properties are considered of more importance. Recommended preheat and interpass temperatures are coded by letters. Preheat and interpass temperature shown for joining dissimilar metals is that recommended for the metal or alloy requiring the highest temperature of the two. Temperatures also vary with the mass and shape of the weldment.

Table 9—Mechanical Properties of Copper and Copper Alloy Weld Metal

Base Metal	Ultimate Tensile Strength, psi. (Av.)	Elongation in 2-In., % (Av.)
	Shielded Metal-Arc Welding	
Copper (deoxidized)	25,000	20
Copper-zinc alloys	30,000–70,000	5–20
Copper-silicon alloys	40,000–46,000	20–25
Copper-tin alloys	40,000–50,000[a]	15–45[a]
Copper-aluminum alloys	70,000–90,000	25–0
Copper-nickel alloys	45,000–50,000	25–30
Copper-beryllium alloys	120,000–136,000[b]	1.5[b]

[a] Hot peened.
[b] Heat treated.
NOTE: See Tables 1–7 for mechanical properties of wrought metals.

or copper should be used. Wide grooves are essential in order to secure proper penetration and avoid slag inclusions (see Fig. 1).

The low-zinc brasses are readily weldable at preheat and interpass temperatures of from 400 to 500°F. However, alloys of high zinc content like Muntz metal, Naval brass and manganese bronze will weld more readily at higher preheats from 500 to 700°F.

All welding should be done in a flat position. When using aluminum bronze (ECuAl-A) electrodes for welding the higher strength brasses, the largest electrode practical should be used with d.c., reverse polarity using the high side of the range. Due to the zinc volatilization, the arc must be concentrated and a small puddle of weld metal started at one point, playing the arc on the deposit and progressing slowly to secure a braze-welding action resulting in a minimum loss of zinc. If possible, the weld metal should be deposited by weaving approximately three times the width of the electrode diameter, pausing at the side walls to fill in undercut, which usually occurs in welding these alloys.

Shielded metal-arc welding of the brasses with phosphor bronze (ECuSn-A) electrodes requires a different technique if maximum mechanical properties are to be obtained in the joints. Preheats are generally lower when using this type of electrode. However, amperages on the high side of the range should be used with fast, thin string beads. Usually, no postheat treatment is necessary.

Copper-Silicon Alloys (Silicon Bronze).—The silicon bronzes are readily weldable by shielded metal-arc welding using either silicon bronze (ECuSi) or aluminum bronze (ECuAl-A) electrodes. Although most fabrication has been done in the past using the carbon-arc process, the use of the metal-arc has increased within recent years because less heat is developed in the joint, minimizing cracking.

Welding is facilitated by the low heat conductivity of these alloys. However, silicon bronzes are hot short and care must be exercised to avoid overheating of the joint. Because the silicon bronzes have lower thermal conductivity than other copper alloys, groove preparations are similar to those used in steel welding. Sheets up to $^{5}/_{32}$-in. thick can be welded with square grooves. Sheets of greater thickness can be prepared with either a single- or double-vee groove having a 60-deg. groove angle. The black oxide remaining on some of the heavier sheets should be removed by grinding. A backing strip of matching plate is desirable.

The silicon bronzes should not be preheated and interpass temperature should be maintained at 150°F. maximum. Rapid welding is required; therefore, with either the silicon bronze (ECuSi) or aluminum bronze (ECuAl-A) electrodes, the weld metal should be deposited in fast, string beads using current in the middle of the recommended range for the size used with a short arc and maintaining a small puddle to avoid excessive overheating of the hot-short base metal. Downhand welding is preferred, although the silicon bronze electrodes can be used in the vertical and overhead positions.

Moderate peening with flat tools will increase mechanical properties of the weld metal and reduce stresses in the joint. No postheat treatment should be used.

Copper-Tin Alloys (Phosphor Bronze).—The tin bronzes are inclined to be hot short and subject to interdendritic shrinkage of the low-melting constituents. They require rapid welding and therefore, shielded metal-arc welding is the most satisfactory means of joining these alloys. Some of the copper-tin alloys contain lead

in rather appreciable amounts; these cannot be welded if quality joints are required.

Two coated electrodes are available for welding these alloys, which can be used interchangeably; they are the phosphor bronze electrodes ECuSn-A and ECuSn-C. The difference is in the tin content of the core wire. Bare electrodes of similar composition are also used although the covered electrodes are preferred because of improved manipulative characteristics and mechanical properties of the deposited metal. Most electrodes are designed for use with d.c., reverse polarity; a.c. electrodes are also available.

The tin bronzes have a tendency to flow sluggishly requiring preheat and interpass temperatures of 300 to 400°F., especially on heavy sections. A backing strip of matching plate is desirable. In the low tin compositions and heavy plate sections, wide grooves are also recommended in order to wash the side walls properly. The current used should be in the middle of the recommended range. All welding should be done in the flat position, if possible, although most electrodes available can be used in the vertical and overhead positions, if necessary.

In groove welding, the first two layers may be deposited using a slight weaving technique; the width of weave should not exceed two electrode diameters. The balance of the layers should be made with fast, thin string beads in order to obtain a dense, fine-grain deposit with maximum mechanical properties, as-welded. Tin bronzes inherently have a coarse, dendritic grain structure which is reproduced in weld deposits resulting in low mechanical properties if proper precautions are not taken in welding. This coarse-grain structure can be refined to some extent by using a string bead technique with a 350° F. preheat and interpass temperature. It can be almost entirely eliminated by hot peening the deposit to produce a fine-grain structure with increased tensile strength and ductility. The short-arc technique similar to that used with covered steel electrodes is recommended. Ordinarily, for most service requirements, postheating is not essential. However, if maximum ductility in the deposit is required, a postheat treatment of 900°F. with fast cooling is recommended.

Copper-Aluminum Alloys (Aluminum Bronze).—Shielded metal-arc welding is used extensively for all grades of aluminum bronze. Five types of covered electrodes are available covering a wide range of compositions and mechanical properties, i.e., ECuAl-A, B, C, D and E, for operation on d.c., reverse polarity; electrodes are also available for welding with alternating current.

The low aluminum content electrodes, ECuAl-A and ECuAl-B, are used for joining commercial grades of aluminum bronze sheet and plate as well as other copper alloys. The deposits have exceptionally good hot strength and hot ductility. The higher aluminum grades, ECuAl-C, D and E, are used to join similar grades of aluminum bronze and to surface bearing and wearing surfaces.

Aluminum bronze cannot be welded with bare electrodes using the metal-arc process because the highly refractory aluminum oxides formed must be removed by fluxing in order to secure a satisfactory deposit. As with the silicon bronzes, a 60-deg. groove angle may be used for heavier sections. A backing strip of matching plate is recommended.

For the low aluminum (soft) grades in heavy sections, a preheat and interpass temperature of 400°F. should be used. For the higher aluminum grades (Rockwell 90B and over), temperatures in the range of 700 to 800°F. should be used to avoid deposit cracking. Welding currents should be in the middle of the recommended range. Groove welding technique is similar to that used in welding steel, except that a slightly longer arc is necessary.

Either weave or string beads may be used with equal success and bead thickness has little effect upon the mechanical properties since the deposits have exceptionally good hot ductility and strength. In other words, the deposit is not hot short like that produced by silicon bronze electrodes. Also, the deposit does not have a tendency to develop a coarse-grain structure like the phosphor bronze electrodes. Downhand welding is, of course, preferred. No postheat treatment is required for the low aluminum grades; an anneal at 1150°F. is required for the high aluminum grades followed by rapid cooling in air.

Copper-Nickel Alloys.—The copper-nickel alloys are metal-arc welded with a heavy covered electrode (ECuNi) having a copper-nickel core wire with a nominal composition of 30% nickel and 70% cop-

per. Its use is limited to the joining of copper-nickel sheet and plate with nickel contents from 20 to 30% and the joining of iron-base metals to copper-nickel alloys.

Like the silicon bronzes a 60-deg. groove angle can be used for heavy sections. Also, these alloys are hot short; therefore, no preheat should be used and interpass temperatures should not exceed 150°F.

Only covered electrodes should be used because the highly refractory nickel oxides formed must be fluxed properly in order to produce quality weld deposits, smooth in appearance and free from slag and porosity. Electrodes operate on d.c., reverse polarity; the middle of the recommended amperage range should be used and welding should be done in the flat position. It is important to remove all slag carefully before applying subsequent layers. The string bead technique is desirable depositing fast, thin layers in order to avoid overheating. Peening moderately with a flat tool is desirable to improve mechanical properties of the deposit and reduce stresses in order to avoid cracking. No postheat treatment is necessary.

Copper - Beryllium Alloys.—Covered beryllium copper electrodes having a nominal core wire composition of 1.1% nickel, 2.50% beryllium and balance copper, are available for metal-arc welding these alloys and for building up wearing surfaces. These electrodes operate on d.c., reverse polarity. Bare electrodes cannot be used to weld the beryllium-copper alloys because of the highly refractory oxides formed. The aluminum bronze electrode ECuA1-A can also be used for the repair welding of beryllium-copper where the higher electrical conductivity of the base metal is not required, and for welding beryllium-copper to dissimilar metals.

The edges of the plate should be prepared for welding with a 90-deg. vee groove for butt welding heavy sections and a root opening sufficiently large to assure 100% penetration. Wherever possible a copper or carbon backing should be used to prevent burning through and collapsing of the metal.

On large masses, a 600 to 700°F. preheat and interpass temperature will aid in obtaining a smooth weld and preventing undercutting. The technique used in welding this alloy is similar to that for aluminum bronze. Work should be positioned so all welding can be done in the downhand position. The weld metal can be deposited in either string beads, or weave beads three to four times the width of the electrode diameter. Since the metal transfer of the beryllium copper electrode is globular and erratic, a slightly longer arc should be used in order to avoid freezing of the electrode. In groove welding the arc length should be increased as side walls are approached in order to obtain a smooth bead and prevent undercutting. Slag should be thoroughly removed between beads. Peening between layers is not necessary but beneficial.

If maximum hardness is to be developed a beryllium copper deposit should be heat-treated in the following manner: Heat to 1450°F. and hold at this temperature for one hour per inch of thickness, water quench and draw at 600°F. for one hour per inch of thickness. The hardness of beryllium copper deposits, as-welded, is 150 to 160 Brinell. After heat treatment, hardness values are approximately 300 Brinell.

Dissimilar Metals.—Bronze electrodes have been used for many years to join dissimilar metals, i.e., steel to brass, cast iron to bronze, steel to cast iron, stainless steel to mild steel, bronze to brass, etc., and for joining *hard to weld* iron-base metals, such as, re-rolled rail stock, cast iron, tool steels, high-carbon steels, etc.

Copper-alloy electrodes are used for this purpose because their lower melting points produce a weld bond with the non-ferrous alloys and a braze-welded bond with the ferrous metals and alloys. It is impossible to secure a quality weld with ferrous electrodes in joining copper-base to iron-base metals.

In welding dissimilar metals, if the base metals to be joined are a copper-alloy and an iron-base metal, an electrode similar to the copper-alloy in composition and/or mechanical properties should be used. If two different copper-alloys are to be joined, a bronze electrode producing a tensile strength within the range of the alloy or metal having the lower tensile strength of the two should be used. There are, of course, exceptions to all rules. However, generally, if this procedure is followed, chances of serious difficulties are minimized. (Consult Table 8 for more detailed recommendations.)

A grooved carbon or copper backing strip should be used to assure complete penetration and prevent burning through of the deposit. Preheat and interpass temperature for joining dissimilar metals is that recommended for the metal or alloy requiring the highest preheat temperature of the two metals being welded.

When copper, brass or beryllium-copper are to be joined to ferrous alloys or metals, the current should be at the high side of the recommended range. If copper-tin, copper-silicon, copper-nickel or copper-aluminum alloys are to be joined to ferrous metals, the middle of the recommended current range is preferred. If two iron-base metals or alloys are to be joined, the low side of the recommended current range should be used.

In joining ferrous to nonferrous metals and alloys, the work should be positioned for welding in the flat position. Satisfactory horizontal fillet welds can be made if the ferrous plate is placed in the vertical plane and the nonferrous plate in the horizontal plane.

The arc is always directed toward the copper-base alloy side of the joint in either fillet or groove welding because the magnetic disturbances set up between two dissimilar metals having wide variations in electrical conductivity or conversely, electrical resistance, tend to pull the arc to the iron-base metal side of the joint.

When welding in a groove with phosphor bronze, silicon bronze or copper-nickel electrodes, string beads are preferred. When welding with aluminum bronze, beryllium-copper or copper electrodes equivalent results can be obtained using either the string or weave bead technique. Peening is beneficial if used moderately. Usually, in dissimilar welding no postheat treatment is required.

Atomic Hydrogen Welding

This process has been used to a limited extent only for welding copper and copper alloys. Welds made by atomic hydrogen welding are characterized by porosity when the copper content is high. Flux is always required and filler metal of the same composition as the base metal is usually used, either cut in strips or drawn into wire form. Tobin bronze has been found to be very satisfactory as filler metal for common brass. (See Chapter 11 for further information on atomic hydrogen welding.)

Inert-Gas Metal-Arc Welding

The advantages of welding by this process are the ability to produce sound welds having high strength and ductility and the ability to confine the weld puddle to a small area by use of high current densities. Fluxes are not required for most applications.

Table 10 gives a list of the welding rods recommended for inert-gas metal-arc welding various base metals.

Copper.—Oxygen-bearing copper may be welded by inert-gas metal-arc welding, although this material is not recommended where best quality welds are required because some amount of porosity is always obtained. If oxygen-bearing copper is welded by this process, a preheat of 400 to 600°F. should be used.

Table 10—Welding Rods Recommended for Use with Various Base Metals for Inert-Gas Metal-Arc Welding

Base Metal	Welding Rod
Copper	Deoxidized copper or copper-silicon
Copper-zinc Copper-silicon Copper-tin	Copper-silicon
Copper-aluminum	Copper-aluminum
Copper-nickel	Copper-nickel, copper-silicon
Copper-beryllium	Copper-beryllium
Iron and steel Cast irons	Copper-silicon, copper-aluminum

Oxygen-free copper may be welded by inert-gas metal-arc welding in thicknesses up to $^1/_2$ inch. A bare welding rod of copper alloyed with small amounts of silicon, manganese and tin will give welds of strength ranging from 29,000 to 30,000 psi. and ductility which will permit a weld in $^1/_2$-in. plate to be bent 180 degrees. Copper-silicon welding rods may also be used. The forehand technique is preferred and either argon or helium without flux may be used. A borax-boric acid flux is recommended for welding pure copper only in thicknesses of $^1/_4$ in. or more.

Copper-Zinc Alloys (Brasses).—Low-zinc or red brass can be welded satisfactorily by the inert-arc process using a copper-silicon welding rod. The amount of zinc fuming may be reduced by machine welding where the speed of welding and the small weld puddle tend to cool the weld more rapidly avoiding the vaporization of the zinc. Either helium or argon can be used as the shielding gas.

Copper-Silicon Alloys (Silicon Bronze).—The advantages of these alloys from a welding standpoint, apply to this process as they do to the other welding processes. In addition the inert-gas metal-arc process eliminates the need for a flux. Welds can be made in material up to 1-in. thick and in all positions of welding. Plates up to $^{3}/_{4}$-in. thick may be butt welded with square edges. Plates $^{3}/_{8}$ to 1 in. thick generally are prepared with a 70-deg. single-vee groove. Either argon or helium may be used with d.c., straight polarity. Welds have shown a minimum of hot cracking and a transverse tensile strength of about 52,000 psi. with an elongation in 2 in. of 50%. Low temperature impact properties of the weld metal and heat-affected zone are good at temperatures down to −325°F.

Copper-Tin Alloys (Phosphor Bronze).—As already indicated these alloys have a tendency toward hot shortness and formation of oxides when heated so that a widespread heating and slow cooling are likely to cause oxides and porosity in weld metal. The inert-gas metal-arc process is suitable for welding these alloys if a small amount of porosity is not objectionable. Either argon or helium may be used with d.c., straight polarity and without a flux.

Copper-Aluminum Alloys (Aluminum Bronze).—These alloys can be welded by the inert-arc process using either helium or argon without flux. A copper-aluminum welding rod is used. Either d.c., straight polarity or a.c. may be used. For a.c. either standard transformers with continuous high frequency stabilization or high open-circuit-voltage transformers designed especially for this process may be used. The former type of equipment should be used with argon only; the latter type may be used with either helium or argon.

Copper-Nickel Alloys.—These alloys can be welded by the inert-arc process with a 70 Cu, 30 Ni welding rod, without a flux. Either helium or argon may be used with d.c. straight polarity or alternating current. For a.c. either standard transformers with continuous high-frequency stabilization or high open-circuit-voltage transformers designed especially for this process may be used. The former type of equipment should be used with argon only; the latter type may be used with either helium or argon.

Copper-Beryllium Alloys.—The same comments as made for copper-nickel and copper-aluminum alloys apply to these alloys.

Dissimilar Metals.—Copper can be welded to silicon bronze using a copper-silicon welding rod. Other combinations of copper alloys which may be welded to each other or to ferrous metals include: copper to steel, cast iron to copper, aluminum bronze to steel and copper to stainless steel. In all cases a copper-silicon welding rod is used; aluminum bronze welding rod also is suitable for these applications except copper to stainless steel.

General.—Typical ranges of current, electrode sizes and gas flows for inert-gas metal-arc welding copper and its alloys are given in Table 11. The specific values to use will vary for each material and for variations in welding procedure. (See Chapter 12 for further information on inert-gas metal-arc welding.)

Submerged Arc Welding

General.—The submerged arc welding of copper and its alloys is complicated by the high thermal conductivities and low melting points of these metals. Suitable granular welding compositions or fluxes have been compounded and techniques for welding have been developed with which butt and fillet welds can be made with

Table 11—Inert-Gas Metal-Arc Welding Copper and Its Alloys

Metal Thickness, In.	Tungsten Electrode Size, In	Helium		Argon	
		Current (D.C. Straight Polarity), Amp.[a]	Gas, Cu. Ft./Hr.	Current (D.C. Straight Polarity), Amp.[a]	Gas Cu. Ft./Hr.
$^{1}/_{16}$	$^{1}/_{16}$	50–125	10–15	60–150	8–12
$^{1}/_{8}$	$^{5}/_{32}$	125–225	14–20	140–280	10–15
$^{3}/_{16}$	$^{1}/_{8}$	200–300	16–22	250–375	12–18
$^{1}/_{4}$	$^{5}/_{16}$	250–350	20–30	300–475	16–25
$^{1}/_{2}$	$^{1}/_{4}$	300–550	25–35	400–600	20–30

[a] When welding with a.c. use about 60 to 70% of these currents.

almost the same facility and economy as they are made in steel. Satisfactory physical and mechanical properties are obtained and the weld metal composition falls within that specified for the base metal. The experience of fabricators and the various laboratories has generally been on plates from $^1/_8$- to $^3/_4$-in. thick which have been welded in either a single pass against a removable backing bar or as a double-vee type butt joint with one pass on either side of the joint. (See Chapter 13 for further information on submerged arc welding.)

Copper.—Submerged arc welding has been used to some extent in the welding of oxygen-bearing copper. Joints should be preheated to temperatures of 600 to 1000°F. depending on the thickness. The filler metal is generally of deoxidized copper with varying percentages of tin and phosphorus.

Table 12 shows typical conditions for single-vee butt welds using a carbon block as a backing, and double-vee butt joints. The electrical conductivity of welds in electrolytic copper bus bar stock is high and the mechanical properties of the joint sufficient for the service.

The submerged arc welding of oxygen-free copper can be readily accomplished in the same manner as outlined for electrolytic copper.

Table 13 shows mechanical properties and weld metal analysis for joints in deoxidized copper.

Copper-Zinc Alloys (Brasses).—Since the zinc present in the brasses fumes at the welding temperatures, submerged arc welding is not recommended.

Copper - Silicon Alloys (Silicon Bronze).—Typical welding conditions for single-vee groove welds in copper-silicon alloys are given in Table 14. The chemical composition of the weld metal is similar to that of the base material in each instance through the use of welding rods of suitable composition. Mechanical properties are given in Table 15.

Table 12—Typical Conditions for Submerged Arc Welding Butt Joints in Copper

Thickness, In.	Type of Joint	Current, Amp.	Voltage, Volts	Speed, In./Min.	Welding Rod Diam., In.	Preheat Temp., °F.	Weld Backing
			Single Pass Butt Joints				
$^3/_{16}$	Sq. butt	550	35	30	$^3/_{16}$	600	Carbon plate
$^5/_{16}$	Sq. butt	600	35–40	15	$^3/_{16}$	800	Carbon plate
			Double Pass Butt Joints				
$^5/_{16}$	Sq. butt[a]	600–700	35–40	25	$^3/_{16}$	650	Welding composition
	Back chip[b]	500	45	25	$^3/_{16}$	650	Main weld

[a] Main weld.
[b] Back weld.

Copper-Tin Alloys.—Little work has been done on the submerged arc welding of these alloys, although some of the lower tin alloys have been successfully welded.

Copper-Aluminum Alloys.—Data are given in Tables 14 and 15 for submerged arc welding copper-aluminum alloys.

Copper-Nickel Alloys.—The 70 Cu, 30 Ni alloy of this type has been submerged arc welded, particularly in the fabrication of marine heat exchangers.

Copper-Beryllium Alloys.—These alloys have not been welded by the submerged arc process so far as is known.

Dissimilar Metals.—Steel may be joined to copper with copper filler metal. Silicon-bronze electrodes are used for joining galvanized parts and produce sound welds of good strength and ductility. Steel and cast iron may be surfaced with a single- or multiple-layer deposit of silicon or aluminum bronze. Careful welding procedures will reduce the penetration into the base metal to a minimum and maintain the iron content of the initial layer at a low level.

Table 13—Mechanical Properties of Submerged Arc Welds In Deoxidized Copper

(Base Metal—ASTM B152-46T, Type B)
Tested As-Welded

Transverse Tensile Coupon	
Ultimate strength.....	32,600–33,200 psi.
Failure.....	In plate
Free-Bend Specimen	
Elongation across weld...	24.2–25.4% without defect

Typical Weld Metal Composition

	Sn	P	Cu
Welding rod	2.7	0.1	Balance
Weld metal	0.85	0.04	99.10

Table 14—Typical Welding Conditions for Submerged Arc Welding Butt Joints in Copper-Silicon and Copper-Aluminum Alloys

Thickness, In.	Edge Preparation — Groove Angle, Deg.	Edge Preparation — Root Face, In.	Current, Amp.	Voltage, Volts	Speed, In./Min.	Welding Rod Diam., In.
		Single-Vee Groove Welds with Copper Backing				
1/8	0	1/8	450	26	75	1/8
1/4	60	1/8	510	35	31	3/16
3/8	60	1/8	700	33	24	1/4
1/2	60	1/8	800	32	20	1/4

Gas Welding

General.—Because the heat obtained from the combustion of other fuel gases such as hydrogen, propane, etc., is not great enough, acetylene is used almost exclusively as a fuel gas for welding copper and its alloys. The other fuel gases are suitable for brazing and soldering. The high flame temperature and heat obtained with acetylene compensate for the high heat conductivity of these metals. On large work it may be necessary to employ additional torches to provide the requisite heat. Flux is usually necessary. In general, the standard joint designs for welding steel apply to these metals also. Filler metals are of the same composition as the base metals although matching weld metal and base metal color may be difficult in those alloys containing low melting constituents which may be lost at welding temperatures. When these metals are used in the cold-worked (hardened) state, the heat of welding will cause annealing in zones adjacent to the welds.

Table 15—Typical Mechanical Properties of Silicon or Aluminum Bronze Welds

	Copper-Silicon	Copper-Aluminum
All-Weld-Metal Tensile Specimens		
Yield strength, psi	19,960	34,600 46,300
Ultimate strength, psi	55,200	60,400 86,200
Elongation in 2 in., %	55	19
Reduction in area, %		13
Brinell hardness, 3000 kg. load		160
Transverse Tensile Specimens		
Ultimate strength, psi	53,400	
Failure	In plate	

Braze welding is also used extensively on the copper and copper base alloys employing filler metal which melts below the melting points of the base metals. Such filler metal is commonly the 60% Cu, 40% Zn alloy. Braze welding is generally acceptable except in those cases where the difference in color is objectionable or in instances where the corrosion conditions preclude the use of the high zinc brass. A flux is, of course, necessary for braze welding. (See Chapter 5 for further information on gas welding.)

Copper.—Oxygen-bearing copper should not be oxy-acetylene welded where strength is a factor for reasons previously enumerated. Since the copper oxide is not present in oxygen-free coppers, they may be used for gas-welded assemblies with the assurance that joint strengths will equal the annealed strength of the base metals—30,000 to 35,000 psi. Welding rods must also be of the deoxidized variety.

Sheets up to 3/16 in. may be welded with square groove butt joints while those of greater thicknesses should be welded with either a single- or double-vee butt joint. A special technique is frequently employed on longitudinal seams in relatively heavy (1/2 to 5/8-in. thick) tanks. The shell is set on end so that the joint is in the vertical position. Two welders, working simultaneously on opposite sides, each weld one-half the thickness, vertically upward. By this method welding time is shortened and preheating is conserved. Copper may be welded with a slightly oxidizing flame in which case the oxide formed serves to protect the molten metal. When flux is used, a neutral flame is indicated and the flux, of course, protects the metal. Supplementary heating, as with additional torches or a charcoal fire, is necessary when welding large sections or heavy thicknesses. Braze-welding with the conventional brass rods and fluxes may also be used for joining copper.

Copper-Zinc Alloys (Brasses).—The low brasses (sometimes called red brasses) are readily welded with the oxy-acetylene flame. Since these brasses are frequently

used for piping, oxy-acetylene welding is particularly suitable because welding may be performed in all positions. Welding rods of the same analysis are not available and best practice calls for the use of 1½% silicon rods as filler metal. This is particularly necessary when resistance to corrosion is a factor. Since these are all alloys of high copper content the welding technique is substantially the same as that given above for copper. Preheating and supplementary heating may also be necessary. Braze-welding with low copper-zinc welding rods is also used but joints so made will not exhibit the same corrosion resistance as the base metal.

The high brasses (frequently referred to as yellow brasses) are readily oxy-acetylene welded. Again much of the brass piping is of these analyses and the ability to weld in all positions makes the oxy-acetylene process well suited for this work. Welding rods of substantially identical analyses are universally available since the brass welding rods (frequently called *bronze rods*) of industry fall in this group. The welding technique is the same as discussed before, including supplementary heating. The use of flux on these compositions is very important, for all the reasons generally stated and also for control of the highly volatile zinc content.

Lead, if present in any of these copper-zinc alloys in amounts greater than about 0.5%, will cause difficulty. The lead, melting at a relatively low temperature, tends to boil out, creating unfavorable welding conditions; porosity may also result.

Copper-Silicon Alloys (Silicon Bronze).—These alloys are successfully welded by the oxy-acetylene process using filler metal of the same composition and flux having a high boric acid content. These welds will exhibit large grains, excellent ductility and tensile strength of the order of 52,000 psi. Oxy-acetylene welds in these alloys are characterized by a viscous film which covers the molten metal. This film is helpful when welding in the vertical and overhead positions. It is desirable to maintain the weld pool as small as is consistent with operations in order to facilitate rapid solidification, thus keeping the grain size small and avoiding contraction strains during the hot-short temperature range. A slightly oxidizing flame will help in maintaining a small weld pool and will not adversely affect the weld metal. Backings are not generally necessary. In welding these alloys with welding rods of the same analysis it is important to assure coalescence of the base metal and the weld metal since it is possible to secure an action which resembles braze welding, but which results in joints of inferior strength. Copper-silicon alloys may, of course, be braze welded with copper-zinc welding rods where the presence of a dissimilar metal is not objectionable.

Copper-Tin Alloys (Phosphor Bronze).—Oxy-acetylene welding is not commonly used for welding the copper-tin alloys because a wide spreading heat accompanied with slow cooling incurs relatively great contraction which may result in cracking and porosity in this hot short material. However, when this process must be used welding rods of Grade E (1.0 to 1.5% Sn) or Grade C (8% Sn) should be used; the latter is used more for hard surfacing. A good flux of the type employed in braze welding must also be used. Normally a neutral flame is preferred unless there is an appreciable amount of lead present, in which case an oxidizing flame will be helpful in reducing unsoundness. Best results are secured when a narrow heat zone is maintained since this promotes quick solidification and enhances soundness.

The phosphor bronzes may, of course, be braze welded with the conventional copper-zinc rods and fluxes, thereby avoiding many of the difficulties encountered when using copper-tin rods. Preheating is desirable when braze welding and essential when welding with the copper-tin rods.

Copper-Aluminum Alloys (Aluminum Bronze).—The aluminum bronzes are rarely oxy-acetylene welded because of the difficulty in handling the aluminum oxide with the conventional fluxes designed for the brasses. Some success has been reported in using a braze-welding flux to which has been added a small amount of aluminum welding flux for the obvious purpose of handling the aluminum oxide. Welding rods should be of the same analysis as the base metal. Braze welding is subject to the same difficulties.

Copper-Nickel Alloys.—From the welding standpoint these alloys are similar to

Monel metal, and oxy-acetylene welding may be used successfully. Flame adjustment should be slightly reducing, i.e., soft. Flux specifically designed for Monel and these alloys is essential to prevent formation of the refractory nickel oxide and avoid porosity. Welding rods must be of the same composition and include sufficient deoxidizer (Mn or Si) to protect the metal during welding. Limited melting of the base metal is desirable in order to facilitate rapid solidification of the molten metal; agitation of the weld should be avoided. The weld once started should be run to the end without stopping and the rod should be maintained continuously in the protective envelope of the flame.

Nickel Silver.—Oxy-acetylene braze welding is the preferred method for joining these alloys which are white in color. The filler metal is a high zinc bronze which contains upward of 10% nickel; it is also white in color. The use of a suitable flux is of the utmost importance to dissolve the nickel oxide and avoid porosity. In this group there is also an extrusion alloy which is high in zinc. When this alloy is joined with the above rod a true weld results.

Copper-Beryllium Alloys.—The welding of these alloys by the oxy-acetylene process is very difficult because of the beryllium oxide which forms. No flux specifically designed to handle this oxide is available, hence metal-arc welding is generally preferred.

Dissimilar Metals.—Dissimilar metals cannot be welded; they may, however, be braze welded with filler metal that melts below the melting points of the dissimilar metals. The high zinc brasses applied with the oxy-acetylene torch are most generally used for this purpose. A suitable braze-welding flux is essential to success in this operation. The surfaces in the area to be braze welded must be cleaned as by grinding or with sandpaper or steel wool. When the dissimilar metals differ greatly in thermal conductivities, the one with the higher conductivity should be afforded some measure of supplementary heating to ensure that it reaches braze welding temperature at about the same time as the other member of the joint. Where the normally yellow color of the deposit is objectionable, as on steel and other *white* metals, high zinc bronze welding rods containing about 10% nickel will provide a reasonably good color match.

Resistance Welding

General.—Most of the copper alloys have electrical and thermal conductivities greater than those of low-carbon steel, hence require a higher welding current, shorter welding time and a lower electrode force than normally used for the same thickness of low-carbon steel. The alloys with the lowest conductivities are the easiest welded.

To be welded satisfactorily, copper and its alloys must be carefully cleaned to remove all oil, grease, oxide and scale, as some of these oxides are quite refractory and consistent results cannot be obtained unless they are removed.

Use of the proper type of electrode material is also of importance. Generally speaking, the high conductivity materials require the use of low conductivity electrodes and vice versa.

Welding machines whether for spot, projection, seam or butt welding must have plenty of electrical capacity to make welds in a minimum length of time as most of these materials are good heat conductors and long welding times tend to heat too large an area with resultant excessive oxidation and distortion. With extremely low energy input, it might be possible to conduct heat away so rapidly that a weld could not be made at all. The moving member of these machines should be as light as possible to reduce inertia, also as free from friction as possible to insure rapid follow-up of pressure application as soon as welding temperature is reached as these materials have little or no plastic range and the machine must follow up rapidly to apply pressure at the proper time and prevent expulsion of molten metal with its attendant cavitation and weak welds (see Chapters 15, 16 and 17).

All machines should be equipped with synchronous electronic controls as the copper and copper alloys are particularly sensitive to variations in welding procedure and this type of control is capable of repeated power applications to the machine with the accuracy of the frequency of the circuit. Synchronous controls also eliminate transient currents sometimes encountered in random switching of power to the welding machine. The current in these transients may be several times the nor-

mal current value and as the heating effect varies as the square of the current, a transient may burn a hole through the work and destroy the electrodes.

Copper.—Pure copper is the least suitable of metals for resistance welding. Spot, projection or seam welding of the various types of copper is very difficult. However, some of the thinner gages are sometimes weldable by the use of electrodes faced with a high resistance material like tungsten or molybdenum. A trace of tin, as in pretinned wire or sheet, is helpful in welding copper. Tinned wire of relatively small size may sometimes be spot or projection welded to other members. Copper may be quite easily butt welded; it does, however, require high energy input and short time with a somewhat special procedure. Generally, the leaded copper alloys do not weld as well as those in which no lead is present.

Copper-Zinc Alloys (Brasses).—Low brass is difficult to weld in comparison with many of the other copper alloys. It requires a low electrode pressure and fairly high energy input. There is some difficulty with electrodes sticking, and strengths are comparatively low. The comparatively high electrical conductivity of these alloys is considered to be the principal cause of the poor results obtained. The same difficulties noted with respect to low brass are encountered, and to a greater degree, with red brass due to its higher electrical conductivity. Through this range of plain brasses it is noticeable that spot welding difficulties increase as the copper content increases.

Common high brass may be welded under a considerable range of welding conditions. The required energy input is, however, on the high side. There is very little electrode sticking except with long welding time and high energy input. Forces over 400 lb. should be used to minimize danger of arcing or blowing through. Cartridge brass is similar to common high brass but it is, in general, more difficult to weld. The greatest difficulty is the tendency for the weld to blow through (explode) at longer welding times and with higher energy input and low welding pressures. Electrode pick-up becomes objectionable under these conditions. Muntz metal is relatively easy to weld in the thin gages and can be welded over a considerable range of conditions. There is little tendency for the electrodes to stick to the work. Due to the high zinc content, forces less than 400 lb. should be avoided.

An improvement in welding quality results from the addition of manganese to red brass. A wider range of welding conditions is permissible, although considerable difficulty is encountered with electrode sticking, particularly after a coating forms on the electrode face. The pickup is more severe where time, pressure and heat are increased. Strength values, however, are high.

Copper-Silicon Alloys (Silicon Bronze).—This appears to be the best of the copper base alloys for resistance welding. It can be welded over a wide range of conditions, with much lower energy input, and there is but slight tendency for electrodes to stick. Short timing (2 to 4 cycles per spot) should be avoided, as it may cause shrinkage voids to occur.

Copper-Tin Alloys (Phosphor Bronze).—This material is similar to silicon bronze and is about equal to silicon brass for ease of spot welding. The range of permissible conditions is wide and the required energy input is low, due to its low electrical conductivity. This alloy is inherently hot short. The welds have good strength with low ductility. Since this alloy is somewhat hot short, cracks may be expected to result from a slight movement of the metal when the metal near the actual weld zone is heated to within the brittle range.

Copper-Aluminum Alloys (Aluminum Bronze, Work-Hardening Type).—The range of welding conditions is only fair, and strength values moderately high. Considerable trouble is experienced with electrode sticking and pickup after some use. This trouble can be reduced by avoiding the use of longer times, and higher currents and pressures. Ductility of the welds is lowered appreciably by age hardening. Recommended spot-welding conditions for the copper-base alloys discussed here, in the 0.036-in. thickness, are given in Table 16. It may be found advantageous to modify these settings to some extent in practice. When settings are changed, test runs should be carried far enough to observe the effect on electrode sticking and pickup, since these factors may seriously influence the production rate.

Table 16—Spot-Welding Conditions for Copper Alloys 0.036-in. Thick[a]

Alloy	Time, Cycles	Force, Lb.	Current., Amp.
Muntz metal	4	400	21,000
High brass	4	400	24,000
Cartridge brass	4	400	25,000
Low brass	[illegible]	400	24,000
Red brass	6	400	25,000
Manganese red brass	[illegible]	400	22,000
Aluminum brass	4	400	24,000
Silicon brass	6	510	22,000
Silicon bronze	[illegible]	400	16,500
Phosphor bronze	[illegible]	510	19,500
Nickel-aluminum bronze	6	400	21,000
Nickel-aluminum bronze (precipitation hardening)	4	510	21,000

[a] RWMA Class 1 electrodes, 3/16-in. diam. tip, 30-deg. approach.

Projection Welding.—Projection welding is not generally recommended for pure copper and for all brasses. The bronzes can be projection welded with satisfactory results for many applications. In the absence of recommended practices the welding conditions for each case must be determined by experiment and will usually involve higher currents, shorter times and lighter pressures than are used for low-carbon steel of the same thickness. Also it will frequently be found that the shape and dimensions of the projections are more critical than for steel.

Seam Welding.—Seam welding of copper is impractical due to its high conductivity and low plastic range; however, many of the copper alloys can be seam welded. They require higher current, slower electrode speed and, in general, lower pressures than low-carbon steel. High pressures cause a demand for so much current that indentation is severe and electrode wear is excessive. However, low pressures should also be avoided since they cause overheating of the electrodes, and because variations in pressure caused by inequalities in the sheet may be too large a proportion of the total pressure. Weld spacings of from 12 to 18 per in. have been found satisfactory.

Flash or Upset Welding.—Copper and all of its alloys may be welded by flash or upset welding in most cases much more easily than by the other resistance welding processes.

Compared with low-carbon steel the high conductivity materials require more current and lower force, and the low conductivity materials approximately the same current and force.

There is very little tabulated information available as to actual welding procedures for flash and upset welding of copper and its alloys. However, with the proper equipment available little difficulty should be experienced in establishing satisfactory welding procedures.

Brazing

Brazing is a very effective means of joining the copper and copper base alloys. Silver brazing alloys (see Chapter 38) having flow temperatures in the range of 1150 to 1600°F. are commonly used; however, alloys having higher flow temperatures and composed essentially of copper and zinc can be used for brazing either pure copper or the high copper alloys.

In general, standard procedures for brazing apply to these copper and copper base alloys. Joint designs which depend on capillary attraction to flow the alloy in the joint are employed and can be of the lap, shear or butt type. Flux will be necessary for most of the metals in this group. Any suitable method for heating which will quickly raise the parts to the brazing temperature can be employed. (See Chapter 22 for further information on brazing.)

Copper.—Oxygen-bearing copper can be brazed readily with no attendant loss of strength due to oxide embrittlement. Lap joints with a lap three times the thickness of the member will develop the full strength of annealed copper. All of the silver brazing alloys can be successfully used with the proper flux. With the copper-phosphorous or the copper-phosphorous-silver brazing alloys no flux is required; however, when flux is used a smoother, better appearing joint results. Heating oxygen-bearing copper in a reducing atmosphere, particularly hydrogen, should be avoided because of a hydrogen-oxygen reaction which takes place. thus embrittling the copper.

Deoxidized or oxygen-free copper like the electrolytic type can be brazed and since no oxide is present, avoidance of a reducing atmosphere is not necessary.

Copper-Zinc Alloys (Brasses).—The *high copper brasses* are readily brazed with silver brazing alloys or certain brasses. Because of their low melting

points, the *low copper brasses* can be brazed with silver alloys only. With either group of brazing alloys a flux is required. For the brass brazing alloys, borax and boric acid are the essential ingredients for effective fluxing at high temperatures. Fluxes, containing fluoride salts, which are active at lower temperatures, are used with the silver brazing alloys.

These brasses are commonly used for piping, because their brazed connections exhibit unusual strength, vibration and corrosion-resistance and can be prepared readily. Occasionally when color match is required as, for instance, in band instruments, it is possible to select a suitable silver brazing composition.

Lead is sometimes added to these brasses to improve their machining qualities. While leaded brasses can be brazed, greater care is required, particularly to insure complete coverage with flux. Lead oxide or *dross* will form and prevent good flow and wetting of the brazing alloy if there is inadequate flux protection. In addition, lead often alloys with the brazing alloy causing it to become brittle.

Copper-Silicon Alloys (Silicon Bronze).—The copper-silicon alloys are brazed readily and, other than the precaution to provide sufficient flux to prevent the formation of the refractory silicon oxide, the usual procedures should be followed. These alloys are subject to intergranular penetration of the brazing alloy if the parts are under stress, and consequently, they should be stress relieved prior to the brazing operation. In practice this stress relief is sometimes accomplished by slowly heating the parts during the brazing operation.

Copper-Tin Alloys (Phosphor Bronze).—No difficulty should be experienced in brazing the various phosphor bronzes. When the tin content is high or there are appreciable lead additions to these bronzes, adequate flux protection during brazing is necessary. The higher melting bronzes can be brazed with the usual brass brazing alloys while all the phosphor bronzes can be brazed with the silver brazing alloys.

Copper-Aluminum Alloys (Aluminum Bronze).—It is possible to braze the various aluminum bronzes, although those having a higher aluminum content present greater difficulty due to the formation of the refractory aluminum oxide. Special fluxes are used with silver brazing alloys, designed particularly to dissolve the aluminum oxide. Certain of these fluxes are not suitable for use on other materials so that when aluminum bronze is brazed to another metal, two fluxes are necessary, one for use on the aluminum bronze and a standard brazing flux for use on the other metal. Some progress is being made in the development of a flux which will be suitable for use on both the aluminum bronze and on the other metal as well.

Copper-Nickel Alloys.—All of the copper alloys containing nickel, i.e., nickel silver and cupro-nickel, are readily brazed employing the usual procedures. The nickel silvers can be brazed with brass brazing alloys but greater care is necessary because of their higher melting temperatures. These nickel alloys, like the copper-silicon alloys, are subject to intergranular penetration of brazing alloy, unless the parts are stress relieved. Care is required during heating to insure uniformity of temperature because of the poor conductivity of these nickel alloys. Since there is a tendency toward overheating, there should be adequate use of flux to prevent the formation of nickel oxide.

Copper-Beryllium Alloys.—These alloys can be joined with silver brazing alloys but extra clean metal is necessary to insure the absence of the very refractory beryllium oxide. Fluxes having a high fluoride content are necessary. While any of the silver brazing alloys can be used with beryllium copper, those having melting points above 1425°F. are required when solution treatment of the beryllium-copper is to follow brazing. Frequently, connections on heat-treated beryllium-copper are required and, in such instances, the brazing should be performed rapidly with the lowest flow point alloys to maintain the best possible mechanical properties. In addition, subsequent aging after brazing of solution-treated beryllium-copper is possible to develop adequate hardness.

Dissimilar Metals.—Dissimilar combinations of the copper alloys can be brazed readily. Care should be exercised when heating metals of different thermal conductivities in order to be certain that both joint members are evenly heated to brazing temperature. When making sleeve connections, the initial clearance of joint should be governed somewhat by the relationship of the coefficients of expansion

of the two parts. If the coefficient of expansion of the outer member is appreciably greater than the coefficient of expansion of the inner member, the initial clearance should be of the order of 0.000 to 0.002 in. to insure good capillary flow of the molten alloy. The initial clearance may be as high as 0.010 to 0.012 in. if the reverse combination exists.

Flow Welding

Flow welding, frequently referred to as *burning in* is the flowing of molten metal of approximately the same chemical composition as the base metal into the joint, washing away and replacing the edges of the metal so as to effect a continuous member upon solidification.

The following description is based on repairs performed by flow welding on cast manganese bronze propeller sections about $1^1/_2$-in. thick and at the section of maximum thickness where the blade joins the hub.

The patch blade should be sufficiently thick to compensate for warpage. In sections less than 3 in., a square butt joint is satisfactory, but for thicker sections a single-vee butt joint with 30-deg. groove angle is preferable. It is important that, when in position for welding, no portion of the face edges shall overhang the root edges, and lines bisecting the groove angle should lie in a vertical plane throughout the length of the joint.

The propeller is positioned on the foundry floor with the pressure face up so that the repair lies generally in the horizontal plane and the patch blade lies in a plane about 2 deg. below the horizontal to compensate for *pull up*. The groove is then surrounded with a suitable mold, for which ordinary green foundry molding sand may be used, (see Fig. 2). The sand should be rammed as hard as practicable and should be channeled out immediately under the joint to provide a semi-circular groove having a radius about one-fourth the thickness of the section being repaired. This groove should be well studded with chill nails to prevent sand-washing. The upper part of the mold

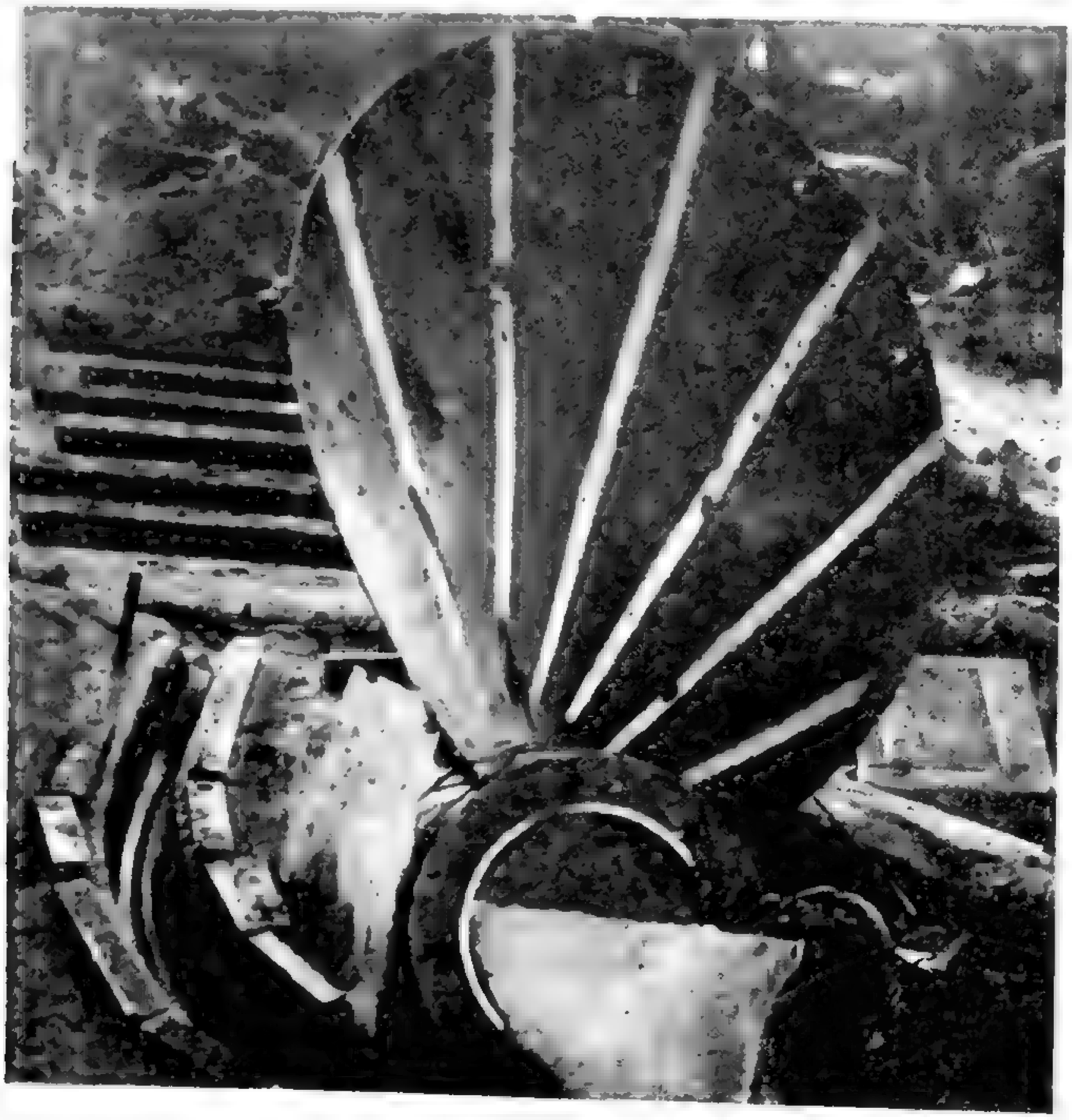


Fig. 2.—Propeller to Be Repaired by Flow Welding Set Up for Pouring Operation

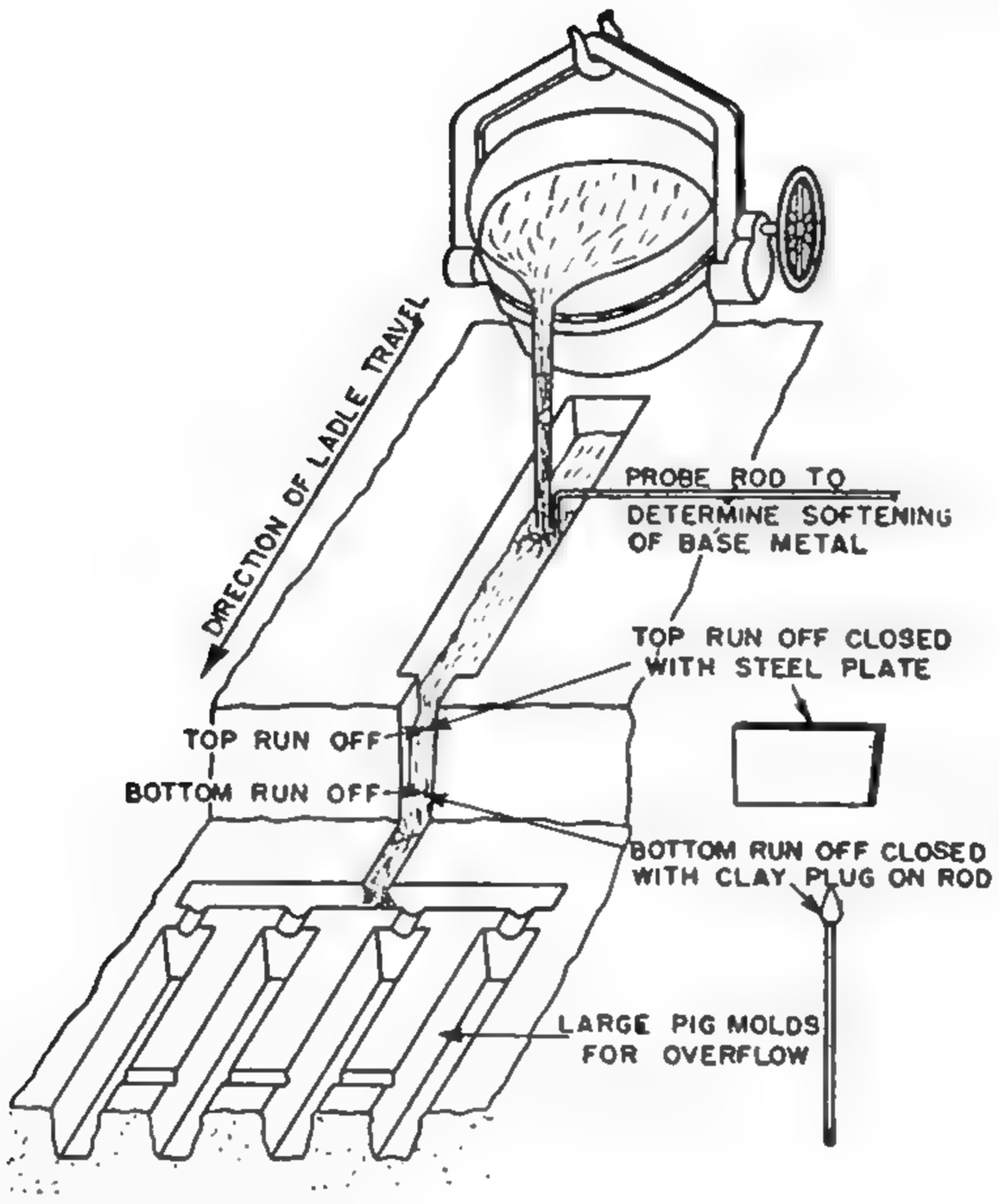


Fig. 3.—Diagrammatic Sketch of Pouring Operation

should be built up above the propeller blade to a height equal to twice the thickness of the blade but in no case less than 6 inches. At the point where the pouring basin joins the upper surface of the blade it should have a width equal to the thickness of the section being repaired, and it should be at least twice this width at the top of the mold. From the pouring basin, a run-off should be provided, the bottom of which is $^1/_2$ in. above the highest point of the surface of the blade. This run-off should be arranged to carry molten metal into a pig bed. A sheet-steel gate should be provided to close this run-off at any desired time thus permitting the formation of a riser or shrink-bead of molten metal extending to the top of the mold. With sections 3-in. thick or over, a 1-in. diam. run-off should also be provided leading from the groove under the joint. Provision should be made for plugging this hole at any time with sand or clay.

A quantity of molten metal, at no less than 1850°F., equal to about 18 to 22 times the volume of the mold, is usually necessary to carry out the welding operation.

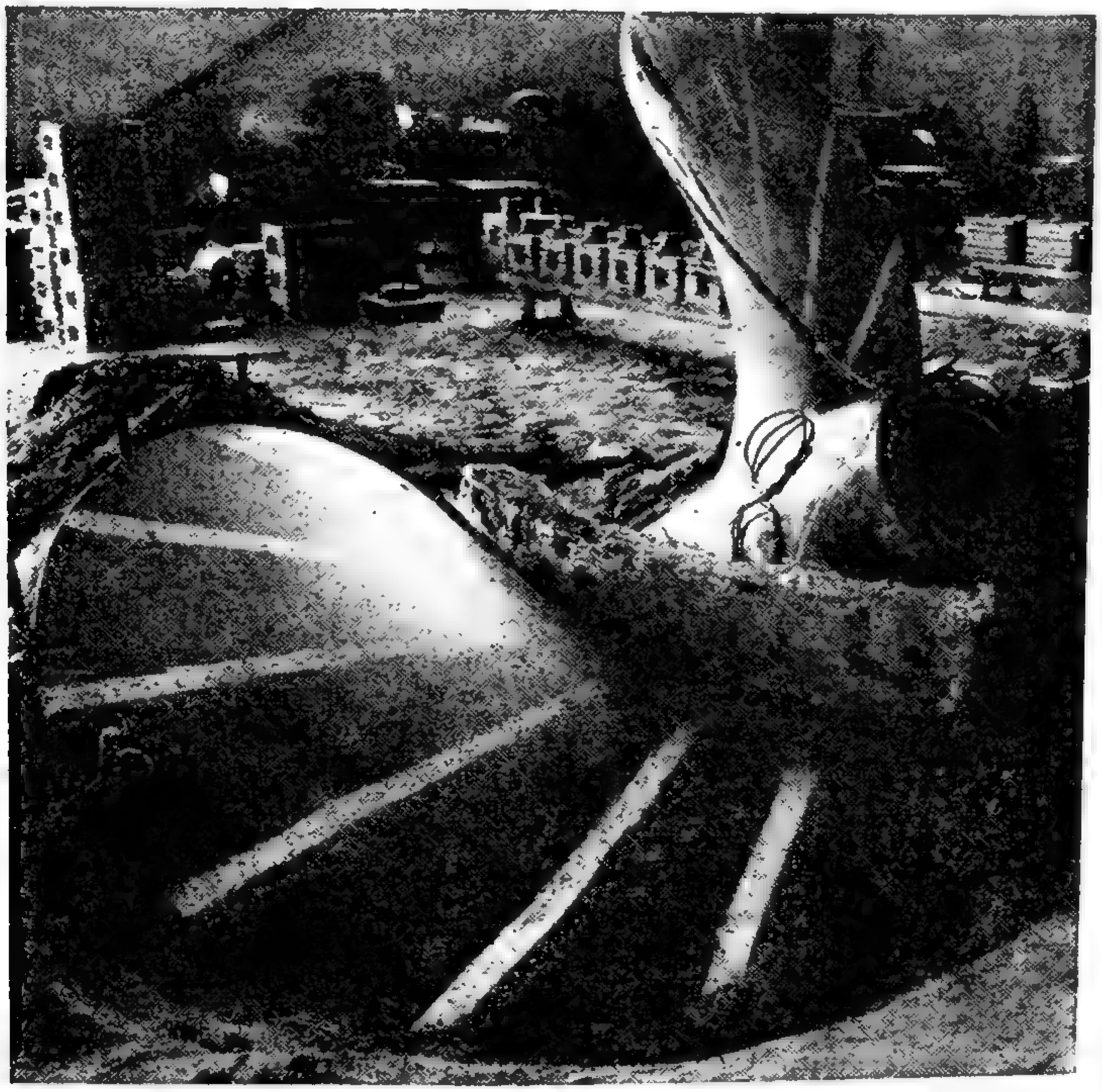


Fig. 4.—Riser on Top of Flow Weld in Propeller

Fig. 5.—Oxy-Acetylene Welded Red Brass Piping

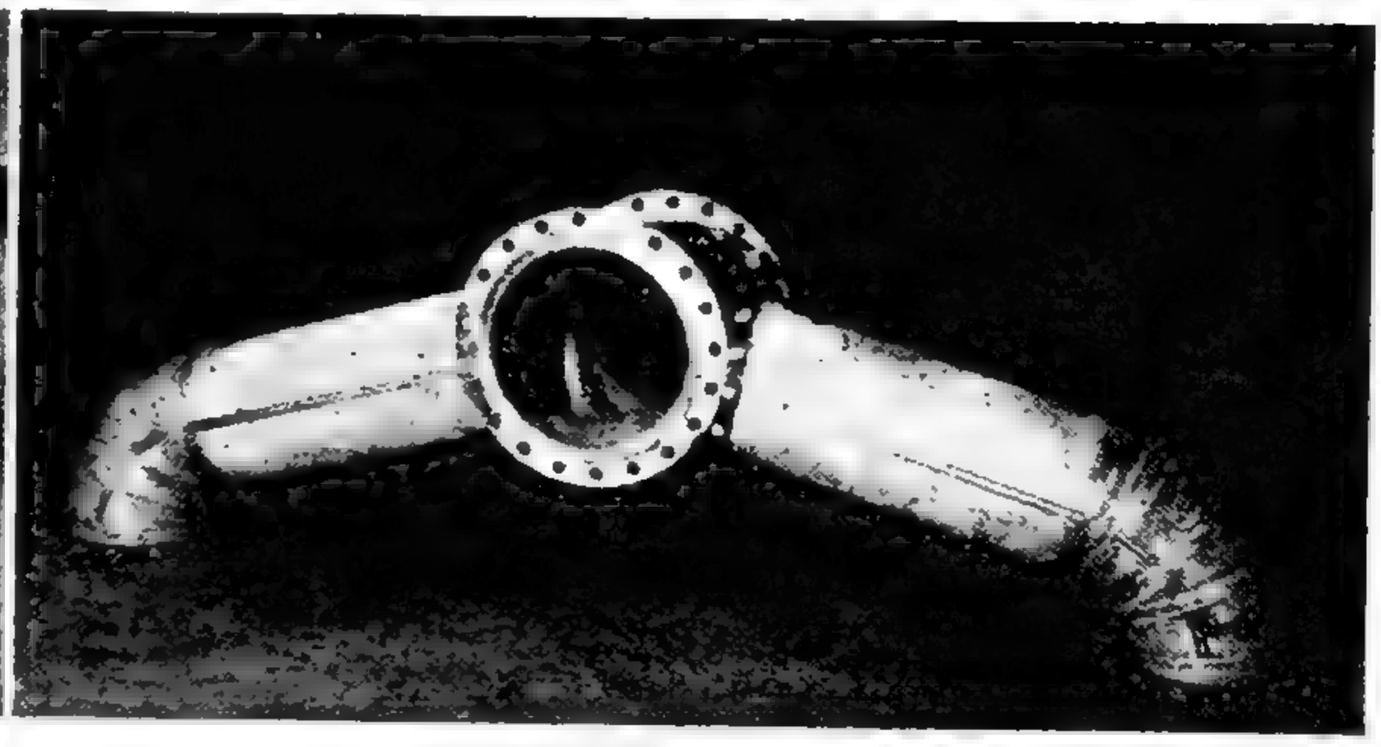


Fig. 6.—Carbon-Arc Welded Copper-Silicon Paper Mill Assembly

The mold should be skin-dried with a torch immediately prior to welding. The ladle should be suspended above the mold no higher than necessary to insure against interference with the other blades, and, as illustrated in Figs. 3 and 4, the stream of molten metal directed into the groove at the end opposite the run-off. The stream is directed onto one spot until softening of the base metal is detected with a $^{1}/_{8}$-in. steel probe rod, and the stream is then progressed along the seam as softening of the base metal progresses. The stream of metal should always be sufficient to maintain the level higher than the base metal with the bottom run-off open if one is used. Should the level fall below the surface of the base metal at any time, the weld will not be sound. When the base metal has been softened throughout the length of the joint, the stream of molten metal is directed back along the weld to wash off the scruff, first plugging the bottom run-off if one is used. The top run-off is then closed and the riser filled to capacity. Should insufficient molten metal be available to complete the weld, the run-offs should be closed and the riser filled. After cooling, the riser and unfused metal may be chipped away and the weld completed in a subsequent operation using the same technique.

Normally welds in propellers are required to be stress relieved; however, due to the fact that hot flow welds will automatically be sufficiently preheated and slowly cooled, stress relief after welding may be omitted.

COMMON APPLICATIONS

Copper alloys are fabricated by welding to form products and structures for many industries. These products include pressure vessels, industrial piping of various sizes including piping for domestic use, and process equipment such as distilling

Fig. 7.—Carbon-Arc Welded Copper Pressure Vessel

units, paper mill stock lines and chemical tanks and other equipment. Copper equipment is also used by the railroads and very small tubing, brazed or soldered, is used in many industries. A few typical applications are shown in the accompanying figures.

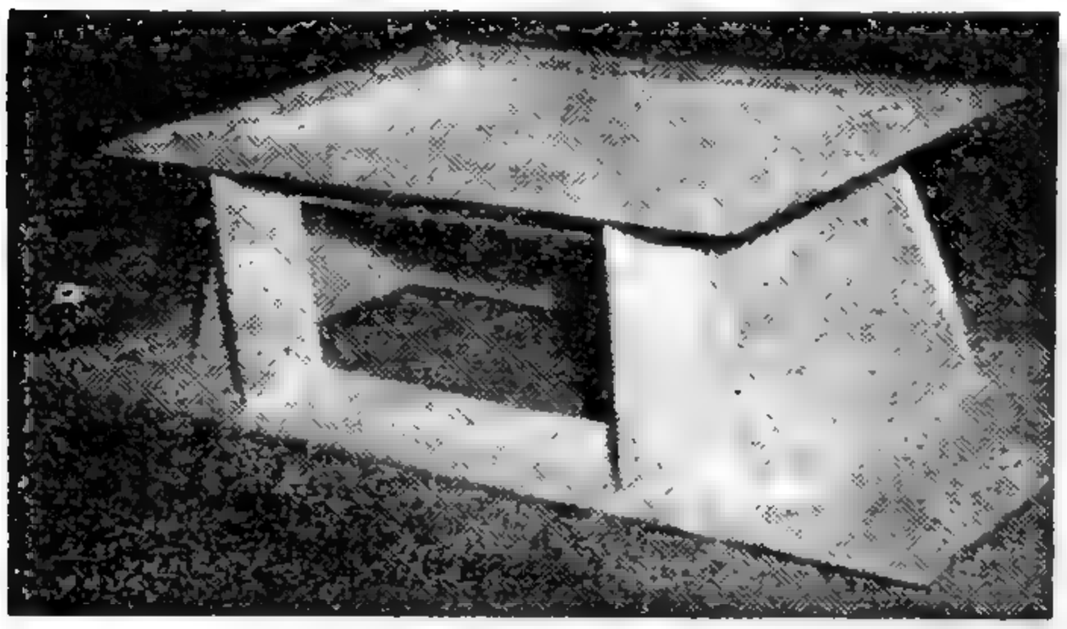


Fig. 8.—Aluminum Bronze Manhole Inlet

Figure 5 shows a red brass piping assembly oxy-acetylene welded in the field using a copper-silicon welding rod.

Figure 6 shows a special paper mill assembly of copper-silicon sheet carbon-arc welded using copper-silicon welding rods. Figure 7 shows the application of carbon-arc welding in the fabrication of a copper pressure vessel (200 psi. test pressure), for which a copper-silicon electrode was used.

Typical applications of shielded metal-arc welding are shown in Figs. 8, 9 and 10. Figure 8 shows an aluminum bronze manhole inlet; Fig. 9 shows a screw conveyor fabricated from aluminum bronze

Fig. 9.—Aluminum Bronze Screw Conveyor

sheet and tubing; Fig. 10 shows an aluminum bronze bearing welded to a mild steel flange. ECuAl-A electrodes were used for all three applications.

The use of inert-gas metal-arc welding is illustrated in Fig. 11, which shows a silicon bronze tank welded with copper-silicon welding rod.

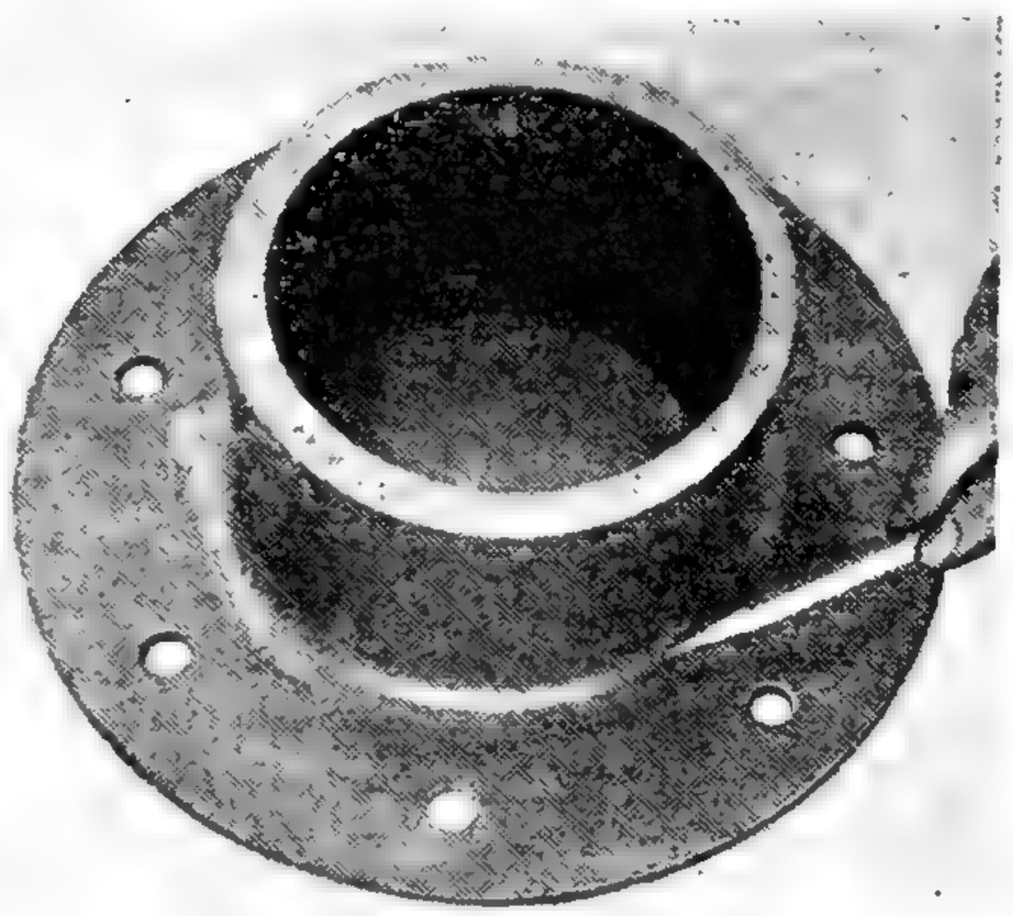


Fig. 10.—Aluminum Bronze Bearing Welded to Mild Steel Flange

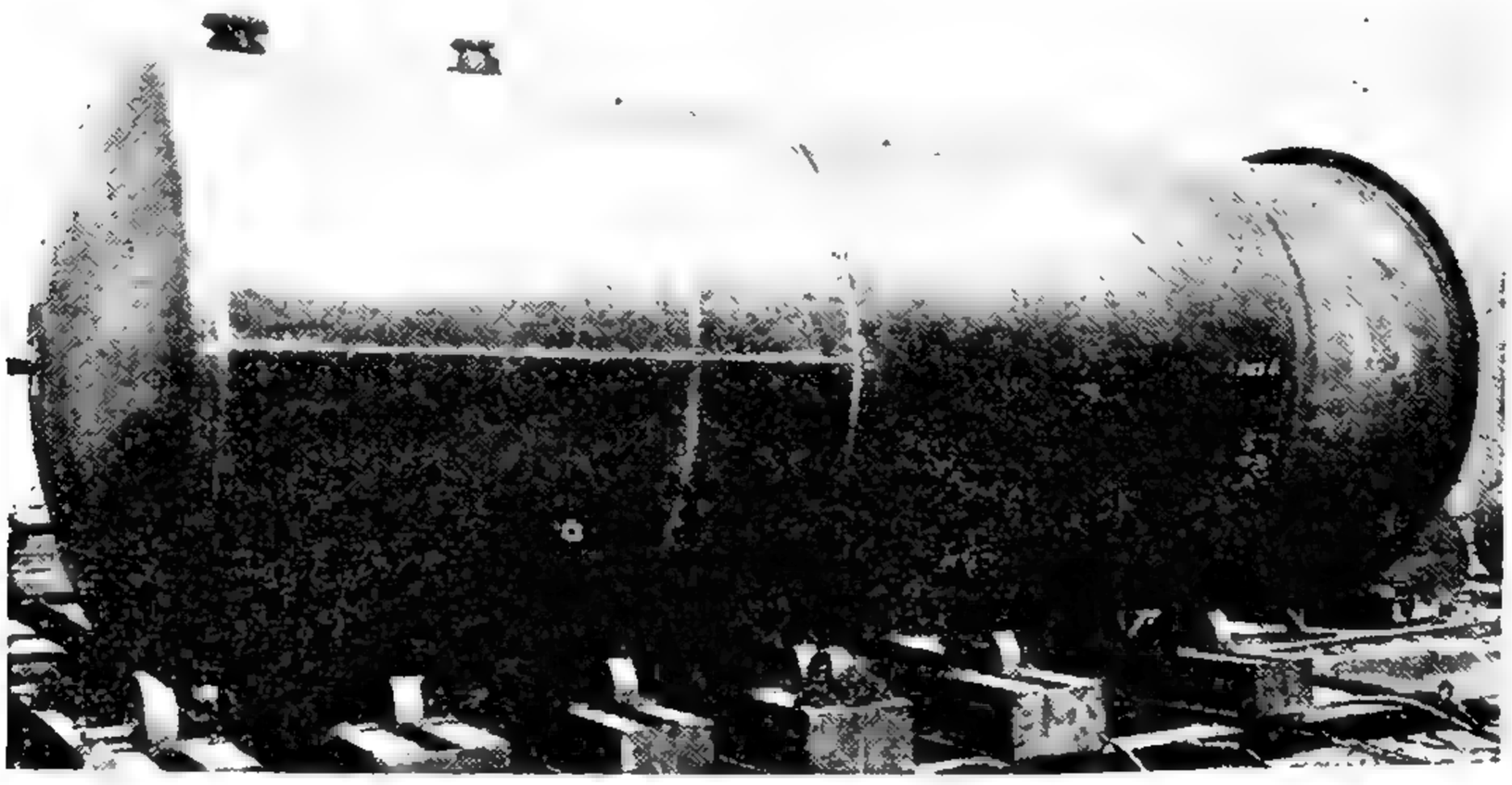


Fig. 11.—Silicon Bronze Tank Fabricated by Inert-Gas Metal-Arc Welding

BIBLIOGRAPHY

1. *Resistance Welding of Copper Alloys,* I. T. Hook, The Welding Journal, December 1935.

2. *Resistance Welding of Dissimilar Metals,* R. T. Gillette, The Welding Journal, October 1936.

3. *The Welding of Copper and Its Alloys* (A Review of the Literature to Jan. 1, 1936), I. T. Hook, The Welding Journal Res. Suppl., February and March 1937.

4. *Spot Welding Characteristics of Some Copper-Base Alloys,* D. K. Crampton and J. J. Vreeland. The Welding Journal Res. Suppl., October 1937.

5. *Data on Spot Welding of 18-8 Stainless Steel to Yellow Brass,* F. R. Hensel, E. J. Larsen and E. F. Holt, The Welding Journal, March 1939.

6. *Pressure Control in Spot Welding of Non-Ferrous Metals,* R. H. Taylor, The Welding Journal, September 1939.

7. *Aluminum Bronze Welds,* W. B. Scott, Steel, November 1940.

8. *A Study of Spot Welding on Copper-Base Alloys,* M. L. Wood, J. Babin, O. B. Atkin, The Welding Journal Res., Suppl., March 1941.

9. *Discussion of a Study of Spot Welding on a Copper-Base Alloy,* C. W. Steward, The Welding Journal Res. Suppl., April 1941

10. *Welding with Aluminum Bronze,* C. E. Swift, The Welding Journal, December 1942.

11. *Resistance Welding Developments and Operations,* R. T. Gillette, The Welding Journal, February 1943.

12. *Welding with Aluminum Bronze,* Roy Norton, The Welding Journal, January 1945.

13. *Electrodes, Welding (Covered), Copper-Aluminum Iron Alloy (Aluminum Bronze) (For Surfacing)* JAN E-278, Army No. 57-203-11, Navy No., 46E7, October 30, 1945.

14. *Reclaiming Bronze Hydro-Burners,* Industry and Welding, May 1945.

15. *Aluminum Bronze Welding in Steel Plant Maintenance,* F. E. Garriott, Iron & Steel Engineer, September 1945.

16. *Welding with Complex Aluminum Bronze Electrodes,* F. C. Evans, A. I. M. and G. Haim, Welding, November 1946.

17. *Arc Welding Brass & Bronze Castings,* Iron Age Welding Manual, February 1947.

18. *Electric Arc Welding of Copper-Base Alloys,* H. H. Hose, Machinery, February 1947.

19. *Weldability of 313 Copper-Base Alloys,* Ampco Metal Inc., 1947.

20. *Electrodes, Welding (Covered), Copper-Aluminum Iron Alloy (Aluminum Bronze), (For General Use)* 46E12 (Ord), June 6, 1947.

21. *Arc Welding of Copper and Copper Base Alloys,* F. E. Garriott, The Welding Journal, October 1947.

22. *Welding with Bronze Electrodes,* Ampco Metal Inc., March 1948.

23. *Silicon Bronze Welded to Steel,* H. H. Hose, The Welding Journal, May 1948.

24. *Bronze Electrode Selection and Preheat Chart,* Ampco Metal, Inc., May 1948.

CHAPTER 35

NICKEL AND HIGH-NICKEL ALLOYS*

GENERAL PROPERTIES

THIS CHAPTER contains detailed information on the joining and properties of commercial forms of nickel, and those of its alloys containing more than 50% nickel. The materials discussed, with trade names and ASTM designations used, where applicable, are shown in Table 1.

A brief general description of these materials follows. Their nominal chemical compositions, physical and mechanical properties are given in Tables 2, 3 and 4, respectively.

Nickel is commercially pure, malleable nickel, with a nominal nickel content of 99.4%. It has high resistance to corrosion and is magnetic.

"L" Nickel is commercially pure, low-carbon nickel. It is used in applications where maximum ductility is required, particularly when exposed to temperatures above 700°F. Its corrosion resistance is the same as that of nickel.

Duranickel† is an age-hardenable, high-nickel alloy in which high strength and hardness are accompanied by high resistance to corrosion. It is slightly magnetic in the age-hardened condition and non-magnetic in the soft condition. Since it is used largely for corrosion-resistant springs, diaphragms or similar flexing parts, welding is employed only incidentally on this material.

Table 1—ASTM Specifications for Nickel and High-Nickel Alloys

	Bar and Rod	Sheet and Strip	Seamless Tubing
Nickel	B-160–41T	B162–41T	B161–41T
"L" nickel	None	None	None
Duranickel	None	None	None
Nickel-copper alloys			
Monel	B164–41T-Class A	B127–41T	B165–41T
"K" Monel	None	None	None
"R" Monel	B164–41T Class B	None	None
"KR" Monel	None	None	None
Nickel-chromium and other high-nickel alloys			
Inconel	B166–41T	B168–41T	B167–41T
Inconel "X"	None	None	None
Heat-resisting alloys	None	None	None
Illium	None	None	None
Hastelloy alloys	None	None	None

Monel is a nickel-copper alloy containing approximately 67% nickel and 30% copper and has high strength, hardness and toughness and good resistance to corrosion. It is slightly magnetic.

"K" Monel is a nonmagnetic, age-hardenable nickel-copper alloy, containing approximately 3% of aluminum. Its strength and hardness, particularly in large sections, are comparable with those of some heat-treated alloy steels, and its resistance to corrosion is similar to that of Monel.

"R" Monel contains approximately twice as much sulfur as Monel, which improves machinability. The additional sulfur does not impair the weldability or corrosion resistance.

* Prepared by a committee consisting of O. B. J. Fraser, The International Nickel Co., *Chairman;* T. J. Featheringham, Youngstown Welding & Engineering Co.; F. G. Flocke, The Thornton Co.; T. S. Gaylord, Eastman Kodak Co.; K. M. Spicer, The International Nickel Co.; R. M. Wilson, Jr., The International Nickel Co.

† Formerly known as *"Z" Nickel.*

Table 2—Nominal Chemical Compositions of Nickel and High-Nickel Alloys

Material	Nickel, %[a]	Copper, %	Iron, %	Chromium, %	Molybdenum, %	Aluminum, %	Silicon, %	Manganese, %	Carbon, %	Sulfur, %
Nickel										
Nickel	99.4	0.10	0.15	..	..	..	0.05	0.25	0.05	0.005
"L" nickel	99.4	0.05	0.1	...	..	..	0.15	0.20	0.01	0.005
Duranickel	93.7	0.05	0.35	..	..	4.4	0.50	0.30	0.17	0.005
Nickel-copper alloys										
Monel	67.0	30.0	1.4	...	..	..	0.10	1.0	0.15	0.01
"K" Monel	66.0	29.0	0.90	.	.	2.75	0.50	0.75	0.15	0.005
"R" Monel	67.0	30.0	1.4	..	..	..	0.05	1.0	0.15	0.035
"KR" Monel	66.0	29.0	0.90	...	..	2.75	0.50	0.75	0.28	0.005
Nickel-chromium and other high-nickel alloys										
Inconel	78.0	0.20	7.0	14.0	.	..	0.25	0.25	0.08	0.007
Inconel "X"[b]	73.0	0.20 max.	7.0	15.0	..	0.70	0.40	0.50	0.04	0.007
Heat-resisting alloys	65–68	...	...	15–19	..	..	...	..	..	...
	59–62	...		10–14		..	...	..	..	...
Illium[c]	60.0	3.0	8.0	21.0	5.0	..	1.0	1.0	..	...
Hastelloy alloy A	53.0	..	22.0	..	22.0	..	1.0	2.0	..	...
Hastelloy alloy B	60.0	.	6.0		32.0	..	1.0	1.0	..	...
Hastelloy alloy C[d]	51.0	.	6.0	17.0	19.0	..	1.0	1.0	..	...
Hastelloy alloy D	85.0	3.0	...	..	..	1.0	10.0	1.0	..	...

[a] Including cobalt [b] Also 1.0% Columbium and 2.5% Titanium. [c] Also 1.0% Tungsten. [d] Also 5.0% Tungsten.

Table 3—Physical Properties of Nickel and High-Nickel Alloys

Material	Density, Gm./Cu. Cm	Density, Lb./Cu. In.	Melting Point, ° F.	Specific Heat, 80–750° F.	Coefficient of Thermal Expansion per ° F., 80–212° F., 10^{-6}	Heat Conductivity B.t.u./Sq. Ft./In./° F./Hr.	Electrical Resistivity Ohms/Cir. Mil Ft. at 32° F.	Modulus of Elasticity In Tension, 10^6 Psi.	Modulus of Elasticity In Torsion, 10^6 Psi.
Nickel									
Nickel	8.89	0.321	2615–2635	0.130	0.72	420	57	30.0	11.0
"L" nickel	8.89	0.321	2615–2635	0.130	0.72	420	50	30.0	11.0
Duranickel	8.26	0.298	2615–2635	0.104	0.72	128	270	30.0	11.0
Nickel-copper alloys									
Monel	8.84	0.319	2370–2640	0.127	0.78	180	290	26.0	9.5
"K" Monel and "KR" Monel	8.47	0.306	2400–2460	0.130	0.78	180	350	26.0	9.5
"R" Monel	8.84	0.319	2370–2460	0.130	0.78	180	290	26.0	9.5
Nickel-chromium and other high-nickel alloys									
Inconel	8.51	0.307	2540–2600	0.109	0.64	104	590	31.0	11.0
Inconel "X"	8.30	0.300	2540–2600	0.110	0.76	87	740	31.0	11.0
Heat-resisting alloys	..	...	2300–2500	...	0.76[a]	94[a]	675[a]	...	..
	..	...	2300–2500	...	0.76[a]	94[a]	675[a]	...	..
Illium	8.31	0.310	2372	0.105	0.51	84	740	...	..
Hastelloy alloy A	8.80	0.318	2372–2426	0.094	0.61	116	763	27.0	..
Hastelloy alloy B	9.24	0.334	2408–2462	0.091	0.56	78	813	30.75	..
Hastelloy alloy C	8.94	0.323	2318–2381	0.092	0.63	87	800	28.50	..
Hastelloy alloy D	7.80	0.282	2030–2048	0.109	0.61	145	681	28.85	..

[a] Approximate.

Table 4—Mechanical Properties of Nickel and High-Nickel Alloys

Material	Form	Condition		Tensile Strength, 1000 Psi.	Yield Strength, 0.2% Offset, 1000 Psi.	Elongation, % in 2 In.	Hardness	
							Rockwell B	Brinell
Nickel								
Nickel	Rods and Shapes'	Hot-rolled,	As-rolled	55–85	15–40	55–35	45–72	90–130
			Forged	60–90	20–60	55–30	54–87	100–170
			Soft	55–80	15–30	60–40	45–68	90–120
		Cold-drawn,	As-drawn	80–115	60–90	35–15	72–93	130–200
			Soft	55–80	15–30	60–40	45–67	90–120
	Sheet		Soft	55–80	15–30	55–35	55–79	101–125
			Hard	90–115	70–105	15–2	92 min.	194 min.
	Strip		Soft	55–80	15–30	55–35	64 max.	114 max.
			Spring	90–130	70–115	15–2	96 min.	215 min.
	Plate	Hot-rolled,	As-rolled	60–100	20–75	45–30	54–93	100–200
			Soft	55–80	15–30	50–35	45–68	90–120
	Tubing	Cold-drawn,	As-drawn	70–95	50–80	35–15	80–100	149–241
			Soft	55–80	15–30	60–40	40–65	85–116
"L" nickel	Rods and shapes	Hot-rolled,	Soft	50–60	10–25	60–40	26–54	75–100
	Sheet		Soft	50–60	10–25	60–40	25–55	75–101
	Plate	Hot-rolled,	As-rolled	55–80	15–60	55–35	45–80	90–150
			Soft	50–60	10–25	60–40	26–54	75–100
Duranickel	Rods and shapes	Hot-rolled,	As-rolled	90–120	35–65	55–30	76–98	140–225
			As-rolled, heat-treated	160–200	120–150	30–15	31–39 C	300–375
		Cold-drawn,	As-drawn	110–150	60–130	35–15	90–32 C	185–300
			As-drawn, heat-treated	170–210	130–175	25–15	32–42 C	300–380
			Soft	90–120	30–60	50–25	74–89	135–185
			Soft, heat-treated	60–190	100–140	30–20	30–38 C	285–360
	Strip		Soft	90–120	35–60	50–30	75–90	136–184
			Soft, heat-treated	160–190	...	25–10	30–40 C	285–363
			Half hard	130–155	...	15–3	25–34 C	250–313
			Half hard, heat-treated	170–210	...	20–7	33–42 C	305–382
			Full hard	155–190	...	10–2	30–40 C	285–363
			Full hard, heat-treated	180–230	...	15–5	36–46 C	329–425
Nickel-copper alloys								
Monel	Rods and shapes	Hot-rolled,	As-rolled (except angles)	80–95	40–65	45–30	76–90	140–185
			Angles	75–90	35–60	45–30	72–86	130–170
			Forged	75–110	40–85	40–20	72–97	130–220
			Soft	70–85	25–40	50–35	62–76	110–140
		Cold-drawn,	As-drawn	85–125	55–120	35–15	84–101	160–250
			Soft	70–85	25–40	50–35	62–76	110–140
	Sheet	Special finish, cold-rolled (0.021 to 0.093 in.)		78–85	45–65	40–20	74–89	134–180
		(Over 0.093 and under 0.021 in.)		70–85	25–45	50–30	61–73	110–132
		Cold-rolled,	Soft	70–85	25–45	50–30	61–73	110–132
			Hard	100–120	90–110	15–2	94 min.	204 min.
	Strip		Soft	70–85	25–45	50–30	68 max.	121 max.
			Spring	100–140	90–130	15–2	98 min.	228 min.
	Plate	Hot-rolled,	As-rolled	75–110	40–90	45–20	80–97	150–220
			Soft	70–85	30–45	50–30	62–76	110–140
	Tubing	Cold-drawn,	As-drawn	85–125	60–120	30–10	85–24 C	164–250
			Soft	70–85	25–45	50–35	60–73	108–132
'K" Monel	Rods and shapes	Hot-rolled,	As-rolled	90–120	40–90	45–25	76–100	140–240
			As-rolled, heat-treated	140–165	100–125	30–20	27–34 C	265–310
			Forged	90–120	40–90	40–25	76–100	140–240
			Forged, heat-treated	140–165	100–125	30–20	27–34 C	265–310
		Cold-drawn,	As-drawn	100–135	70–100	35–13	88–26 C	175–260
			As-drawn, heat-treated	140–170	100–130	30–15	27–35 C	265–320

			Soft	90–110	40–60	45–35	76–89	140–180
			Soft, heat-treated	130–150	90–110	30–20	22–30 C	240–280
	Sheet	Cold-rolled,	Soft	90–105	40–65	45–25	75–85	136–165
			Soft, heat-treated	130–150	90–110	25–10	20–30 C	228–285
	Strip		Soft	90–105	40–65	45–30	75–85	136–165
			Soft, heat-treated	130–150	90–110	25–10	20–30 C	228–285
			Half hard	125–145	85–105	20–10	15–28 C	206–275
			Half hard, heat-treated	150–180	110–130	15–5	28–35 C	275–321
			Full hard	145–165	105–120	8–2	25–32 C	255–298
			Full hard, heat-treated	170–200	125–145	10–2	33–40 C	305–363
"R" Monel	Rods and shapes	Hot-rolled,	As-rolled	75–90	35–60	45–25	72–86	130–170
		Cold-drawn,	As-drawn	85–115	50–100	35–15	84–98	160–230
"KR" Monel	Rods and shapes	Hot-rolled,	As-rolled	90–120	40–90	45–25	76–95	140–210
			As-rolled, heat-treated	140–160	90–120	30–20	25–32 C	265–300
		Cold-drawn,	As-drawn	100–135	70–100	35–13	88–102	175–260
			As-drawn, heat-treated	140–170	100–130	30–15	25–35 C	265–320
			Soft	90–110	40–60	45–35	76–89	140–180
Nickel-chromium and other high nickel alloys			Soft, heat-treated	130–150	90–110	30–20	22–30 C	240–280
Inconel	Rods and shapes	Hot-rolled,	As-rolled	85–120	35–90	50–30	76–95	140–210
			Forged	85–120	35–90	45–25	76–95	140–210
			Soft	80–100	25–50	55–35	67–86	120–170
		Cold-drawn,	As-drawn	95–150	70–125	30–10	80–32 C	180–290
			Soft	80–100	25–50	55–35	67–86	120–170
	Sheet	Cold-rolled,	Soft	80–100	30–45	55–35	76–88	139–176
			Hard	125–150	90–125	15–2	21–26 C	232–260
	Strip		Soft	80–100	30–45	55–35	84 max.	161 max.
			Full hard	140–170	100–160	10–2	27 C min.	265 min.
	Plate	Hot-rolled,	As-rolled	90–110	45–95	40–20	84–100	160–240
			Soft	80–110	30–60	50–35	67–86	120–170
	Tubing	Cold-drawn,	As-drawn	110–160	70–140	25–2	8–35 C	180–321
			Soft	80–100	30–50	55–35	65–85	116–165
Inconel "X"	Round Rods and Flats	Hot-rolled		.....	.....	...	76–32 C	140–300
		Hot-rolled or forged, and aged		165–200	125–150	25–15	33–44 C	305–400
		Hot-rolled or forged, solution treated		150–175	90–125	25–15	25–38 C	260–340
	Sheet and Strip	Cold-rolled,	Soft	105–125	30–60	40–25	76–89	140–180
			Soft and aged	150–175	90–125	25–15	25–38 C	260–340
Heat Resisting Alloys								
60 Ni, 15 Cr		Hot-rolled		110	60	35	93	200
80 Ni, 20 Cr		Cold-drawn, annealed		110	60	35	.....	.....
					Elastic Limit			
Illium "G"		Cast		60–73	50–63	...	84–95	160–210
"R"		Rolled (annealed)		95–105	45–55	30–45	88–100	175–240
					Yield Strength			
Hastelloy alloy A		Cast		69–77	42–45	8–12	85–94	155–200
		Rolled (annealed)		110–120	47–52	40–48	94–97	210–215
Hastelloy alloy B		Cast		75–82	55–57	6–9	92–99	190–230
		Rolled (annealed)		130–140	60–65	40–45	96–100	210–235
Hastelloy alloy C		Cast		72–80	45–48	10–15	89–97	175–215
		Rolled (annealed)		115–128	55–75	25–50	84–95	160–210
Hastelloy alloy D		Cast		36–40	.....	0	50–55	95–102

"KR" Monel, like K Monel, is an age-hardenable alloy but with improved machinability.

Inconel is a rolled, high-strength, non-magnetic, nickel-chromium-iron alloy containing approximately 78% of nickel and 14% of chromium. Because of freedom from scaling and intercrystalline attack, it has been used extensively for service at elevated temperatures.

Inconel X is a non-magnetic, age-hardenable alloy containing aluminum, columbium and titanium as hardening agents. It has superior mechanical properties at temperatures up to 1500°F. In resistance to corrosion and high-temperature oxidation it approximates Inconel.

The Hastelloy alloys consist of four types of nickel-base alloys, designated as A, B, C and D. Developed primarily for resistance to the corrosive mineral acids, they also possess very good mechanical properties. These properties are given in Table 4, and compositions and physical constants are given in Tables 2 and 3, respectively.

Hastelloy Alloy A is a nickel-molybdenum-iron alloy which is as strong as some alloy steels and is particularly resistant to hydrochloric and sulfuric acids. It is made in the following forms: castings, wrought parts, rolled sheet, wire and welded tubing.

Hastelloy Alloy B is a nickel-molybdenum-iron alloy with higher molybdenum content than Hastelloy A. It is used for equipment handling boiling hydrochloric acid, wet hydrochloric acid gas and sulfuric acid. It is made in the same forms as Hastelloy A.

Hastelloy Alloy C is a nickel-molybdenum-chromium-iron alloy capable of withstanding strong oxidizing agents. It is available in the same forms as alloys A and B.

Hastelloy Alloy D, available in cast form only, is an alloy of nickel and silicon plus small amounts of other metallic elements. It is exceptionally resistant to sulfuric acid in all concentrations and at all temperatures up to boiling.

Illium is an alloy composed of nickel and chromium, with small amounts of copper, molybdenum, manganese and tungsten. It was developed primarily for resistance to sulfuric, phosphoric and nitric acids over a wide range of concentration and exposure conditions. Illium G is the cast form; *Illium R,* having the same general composition, is produced in wrought form as rolled strip, sheets, plates, clad steel, welded tubing and wire. Its nominal composition, physical constants and mechanical properties are given in Tables 2, 3 and 4.

Nickel-chromium-iron heat-resisting alloys are chemically and mechanically stable at elevated temperatures and have good resistance to oxidizing, reducing and other high-temperature, corrosive atmospheres. These materials are produced in castings, sheet and wrought bars, and are used particularly in oil refinery stills, steel mill and heat-treating furnace parts, carburizing boxes, chemical processing equipment, in the glass industry and for other high-temperature applications.

Heat-resisting alloys are manufactured under a variety of trade names by many companies. Some of the better known are:

Amsco F5—American Manganese Div., American Brake Shoe Co.
B & W's 700 and 701—Babcock and Wilcox Co.
BTG Steel and Midvaloy BTG—The Midvale Co.
Calite N—The Calorizing Co.
Chromel C—Hoskins Mfg. Co.
Empire 60-20—Empire Steel Castings, Inc.
Fahrite N 5—Ohio Steel Foundry Co.
Fernite No. 1—The Forging & Castings Co.
Firearmor A and B—Michiana Products Corp.
Misco HN—Michigan Steel Castings Co.
Nichrome I, II, III, IV—Driver-Harris Co.
Par 8—Crucible Steel Casting Co.
Primer C—Alloy Metal Wire Co.
Q Alloy A and B—General Alloys Co.
Standard Alloy HR4—Standard Alloy Co.
Sweetalloy 21—Cooper Alloy Foundry Co.
Thermalloy A—Electro Alloys Co.
Tophet C—Wilbur B. Driver Co.
Westeeco No. 5—Western Crucible Steel Casting Co.

HOW TO WELD

General Considerations

Selection of Process.—The joining processes that are used for steel are applicable, though sometimes with slight modification, to nickel, "L" nickel, Monel, "K" Monel, Inconel and Inconel "X." Duranickel, "R" Monel and "KR" Monel are seldom

used in applications where welding is involved. The processes are tabulated below and discussed at length in succeeding subsections.

Welding and Allied Processes:
- Shielded Metal-Arc Welding
- Atomic Hydrogen Welding
- Inert-Gas Metal-Arc Welding
- Submerged Arc Welding
- Carbon-Arc Welding
- Stud Welding
- Oxy-Acetylene Welding
- Brazing
- Braze Welding
- Soft Soldering
- Spot Welding
- Seam Welding
- Projection Welding
- Flash Welding
- Pressure Gas Welding
- Gas and Arc Cutting

Since each welding process produces satisfactory joints, when applied properly, the choice in each case is determined by:

1. The corrosive environment to which equipment will be exposed (to establish whether welding, brazing or soft soldering is applicable).
2. The thickness of material being joined.
3. The required joint strength.
4. The accessibility of individual joints and the contour of parts to be joined.

Gas welding with fuel gases other than acetylene is not practicable for welding of nickel or high-nickel alloys because the temperatures attainable are too low.

Hammer welding is not possible.

Good properties are inherent in welded joints in all the high-nickel materials and no after-treatment, either thermal or chemical (passivation), is needed or recommended to retain or restore corrosion resistance. The joints are equivalent in corrosion resistance and strength to the base metal. Thermal treatments, however, may be applied for special reasons, as for example, stress relief of a welded Monel structure to meet code requirements, or an age-hardening treatment to increase strength and hardness in Duranickel, "K" Monel or Inconel "X."

Since the coefficients of expansion of these high-nickel materials are all about equal to that of steel, warping and buckling resulting from a welding operation will be about the same as would be encountered in a similar steel weldment. The mechanical properties of the various types of joints are to be found in the sections describing the use of each process for joining the nickel and nickel alloys.

Cleanliness.—Electrodes, welding rods and fluxes for nickel and nickel alloys have been developed for use on clean metal, such as standard cold-rolled sheet, pickled hot-rolled plate or cold-drawn rod. The removal of all machining lubricants, dirt, grease, oil, paint, marking crayon and processing chemical residue (on used material) is essential before starting to weld. Nickel and nickel alloys are highly susceptible to embrittlement by sulfur and lead. All of the foregoing materials are liable to contain either or both of those elements. Partial removal is unsatisfactory. To insure satisfactory welding of hot-rolled plate, hot-rolled bar stock or material that has been otherwise hot worked in processing or fabrication, it is necessary, first, to remove the thin, dark-colored oxide film from the immediate vicinity of the area to be welded, either mechanically by machining, sandblasting, grinding or rubbing with emery cloth, or chemically by pickling. Difficulty in the form of an unstable arc may be encountered if the oxide is not removed. A hot-rolled plate that has been beveled by machining in preparation for a butt joint needs no further cleaning, because a clean metal surface is exposed on the groove face.

Joint Preparation.—The joint designs applicable in fabricating nickel and high-nickel alloys are essentially those used for welded fabrication in plain carbon steel. Suggested joint welding procedures for nickel, Monel and Inconel are given in Tables 5 and 6.

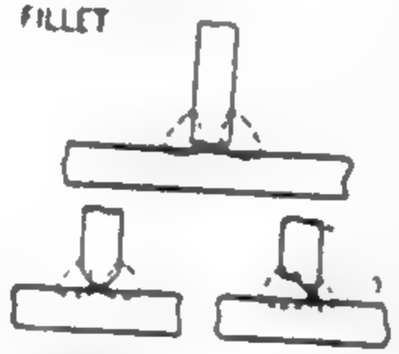
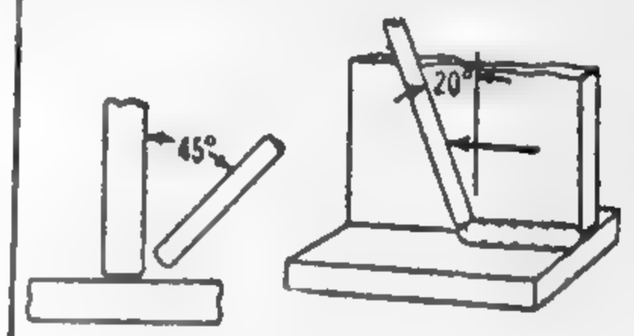
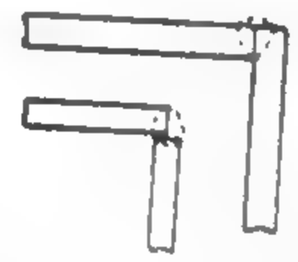
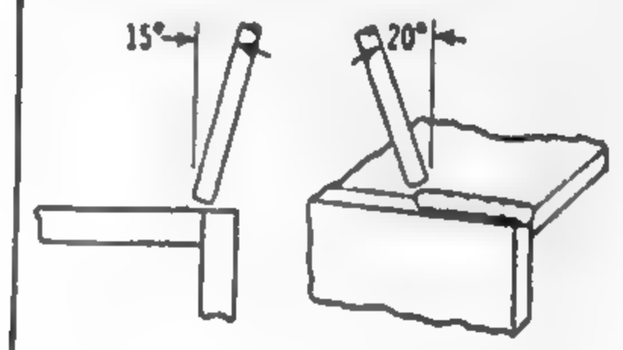
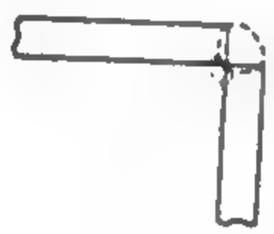
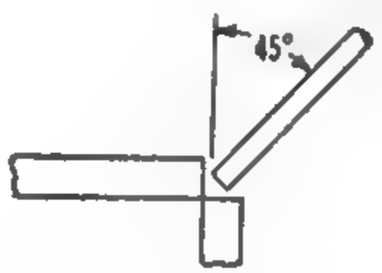
Corner and lap joints may be welded where high stresses are not encountered, but are not suitable for equipment that is to be used at elevated temperatures. In equipment such as pressure vessels, butt joints are preferred over lap joints.

Beveling is not recommended for sheets 0.125 in. or less in thickness. For thicker material, a bevel angle of 37½ deg. (75 deg. groove angle) for vee grooves, and 15 deg. for U and J grooves should be used. In all cases, it is desirable to retain a root face of 1/16 in., or slightly more.

To obtain uniform and accurate fit-up, chamfering is done best by machine, usually a planer. Neither conventional oxy-acetylene nor carbon-arc cutting is

Table 5—Joint Geometries for Manual Arc-Welding Data for Nickel, Monel and Inconel

Joint Type 100% Penetration is Assumed	Minimum and Maximum Gauges (U.S.S.) for Various Positions		Root Spacing "S" Between Plates in Column 1		Joint Backing—(Copper Bars Are Preferred)	Tack Welds	Electrode Diameter *		No of Passes Required to Complete the Joint	Electrode Positions for Downhand Welding End and Side Views
	Min.	Max.	For Min. Gauge	For Max. Gauge			For Min. Gauge	For Max. Gauge		
SQUARE BUTT	(f) .037″ (20 ga.)	.125″ (11 ga.)	0	1/16″	Backing is necessary for gauges .050″ (18 ga. U.S.S.) and thinner — If design permits, backing should be	1/8″ Long on 3 -4″ Centres	.075″	1/8″	1	Electrode Travel, Electrode
	(v) .062″ (16 ga.)	.125″ (11 ga.)	0	1/16″			.075″	1/8″	1	
	(o) .050″ (18 ga.)	.125″ (11 ga.)	0	3/32″			3/32″	1/8″	1	
SINGLE "V" BUTT, 75°, S, OR	(f) 5/32″ (9 ga.)	5/16″	1/16″	3/32″		1/4″-1/2″ Long on 6″ Centres	1/8″	5/32″	1 for 5/32″ or 3/16″ Plate 2 for 1/4″ Plate 3 for 3/8″ Plate 3 or 4 for 7/16″ & 1/2″ Plate	
	(v) 5/32″ (9 ga.)	3/8″	1/16″	3/32″			1/8″	5/32″		
	(o) 5/32″ (9 ga.)	5/16″	1/16″	3/32″			1/8″	5/32″		
SINGLE "V" (WITH LIP) BUTT, 75°, t, 1/4 t	(f) 5/32″ (9 ga.)	1/2″	1/16″	1/8″		1/4″-1/2″ Long on 6″ Centres	1/8″	3/16″		
	(v) 3/16″ (7 ga.)	7/16″	1/16″	1/8″			1/8″	3/16″		
"U" GROOVE BUTT, 15°, 1/16 R, S, Lip 1/32″	(f) 1/2″	No Max.	1/16″	3/32″		1″ Long on 8″ Centres	1/8″	5/32″ & 3/16″	Depends on Plate Thickness	30°, 30°, 20°
	(v) 1/2″	No Max.	1/16″	3/32″			1/8″	5/32″ & 3/16″		
LAP	(f) .037″ (20 ga.)	No Max.	None			1/4″ Long on 6″ Centres	.075″	5/32″ or 3/16″	1 or More	40°, 20°
	(v) .062″ (16 ga.)	No Max.	None				.075″	5/32″ or 3/16″		
	(o) .062″ (16 ga.)	No Max.	None				.075″	5/32″ or 3/16″		

FILLET 	(f) .062″ (16 ga.) (v) .062″ (16 ga.) (o) .062″ (16 ga.)	No Max. No Max. No Max.	None None None	provided for gauges .062″ (16 ga. U.S.S.) to .093″ (13 ga. U.S.S.)	¼″-½″ Long on 6″ Centres	3/32″ 3/32″ 3/32″	5/32″ or 3/16″ 5/32″ or 3/16″ 5/32″ or 3/16″	1 or More	
CORNER 	(f) .050″ (18 ga.) (v) .062″ (16 ga.) (o) .062″ (16 ga.)	⅛″ (11 ga.) ⅛″ (11 ga.) ⅛″ (11 ga.)	None None None		¼″ Long on 4″ Centres	.075″ .075″ .075″	⅛″ ⅛″ ⅛″	1 1 1	
CORNER 	(f) 3/32″ (13 ga.) (v) 3/32″ (13 ga.) (o) 3/32″ (13 ga.)	No Max. No Max. No Max.	None None None		¼″ Long on 4″-8″ Centres	⅛″ ⅛″ ⅛″	5/32″ or 3/16″ 5/32″ or 3/16″ 5/32″ or 3/16″	Depends on Plate Thickness	
	(f) .037″ (20 ga.)	.062″ (16 ga.)	None		⅛″ Long on 4″-8″ Centres	.075″	3/32″	1	Same as for Square Butt (at top of table)
Grind Only to Sound Metal	(f) .031″ (22 ga.)	.050″ (18 ga.)	None		⅛″ Long on 4″-8″ Centres	.075″	3/32″	1	Same as for Square Butt (at top of table)

(f) = Flat Position (v) = Vertical Position (o) = Overhead Position

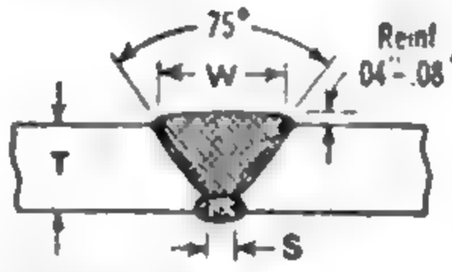
* See also Table 7.

Table 6—Joint Welding Procedures for Manual Arc Welding Nickel, Monel and Inconel

Type of Joint	Sheet or Plate Thickness "T" inches	Width of Bead (or Groove) "W" inches	Root Spacing "S" inches	Average Amount of Metal Deposited per Linear Foot cu. in.	Average Amount of Metal Deposited per Linear Foot lb.	Approximate Weight of Electrode Required lb. per Linear Foot (see Note 2)
SIMPLE BUTT Reinforcement .03"-.06" Removeable Copper Backing	.037	1/8	0	.07	.02	.025
	.050	5/32	0	.13	.04	.05
	.062	3/16	0	.13	.04	.06
	.093	3/16–1/4	0–1/32	.18	.06	.08
	.125	1/4	1/32–1/16	.22	.07	.09
SQUARE GROOVE Reinforcement .03"-.07"	1/8	1/4	0-1/32	.35	.11	.15
	3/16	3/8	1/32–1/16	.74	.24	.32
	1/4	7/16	1/16–3/32	.97	.31	.42
"V" GROOVE 75° Reinf. .04"-.08" 1/16" Lip Removeable Copper Backing	3/16	.30	1/8	.72	.227	.31
	1/4	.45	3/16	1.39	.443	.61
	5/16	.54	3/16	1.84	.582	.80
	3/8	.63	3/16	2.36	.745	1.02
	1/2	.90	3/16	3.68	1.16	1.59
	5/8	.97	3/16	5.10	1.61	2.21

Type of Joint	Sheet or Plate Thickness "T" inches	Width of Groove "W" inches	Size of Fillet "L" inches	Average Amount of Metal Deposited per Linear Foot cu. in.	Average Amount of Metal Deposited per Linear Foot lb.	Approximate Weight of Electrode Required lb .per Linear Foot (see Note 2
BEVEL GROOVE Reinforcement .04"-.08" 45° 1/8" Lip See Note 1	1/4	.125	....	.22	.07	.09
	5/16	.188	....	.40	.13	.17
	3/8	.250	....	.61	.19	.26
	1/2	.375	....	1.21	.38	.52
	5/8	.500	....	1.98	.63	.86
	3/4	.625	....	2.95	.93	1.28
	1	.875	....	5.57	1.77	2.42
DOUBLE "J" GROOVE Reinf. .04"-.08" 15° 1/8" Lip 1/2" R See Note 1	1	.500	....	4.67	1.48	2.0
	1 1/4	.563	....	6.90	1.90	2.6
	1 1/2	.594	....	8.10	2.56	3.5
	1 3/4	.625	....	9.83	3.11	4.3
	2	.656	....	12.06	3.81	5.2
	2 1/4	.688	....	14.29	4.51	6.2
	2 1/2	.750	....	16.68	5.27	7.2
DOUBLE BEVEL GROOVE Reinf. .04"-.08" 1/8" Lip 45° See Note 1	1/2	.188	....	.78	.25	.34
	5/8	.250	....	1.24	.39	.54
	3/4	.313	....	1.78	.56	.77
	1	.438	....	3.13	.99	1.36
	1 1/4	.563	....	4.87	1.54	2.15
	1 1/2	.688	....	7.00	2.21	3.03
	1 3/4	.813	....	9.47	3.00	4.09
	2	.938	....	12.33	3.90	5.35

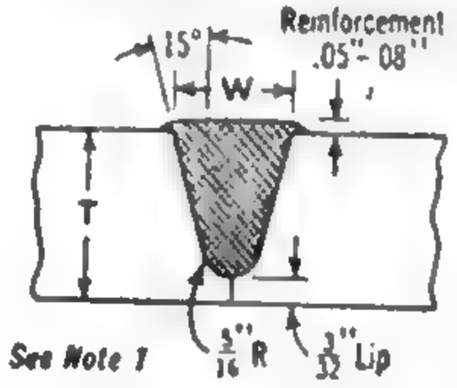
"V" GROOVE



No Backing Used.
Under Side of Weld Chipped and Welded

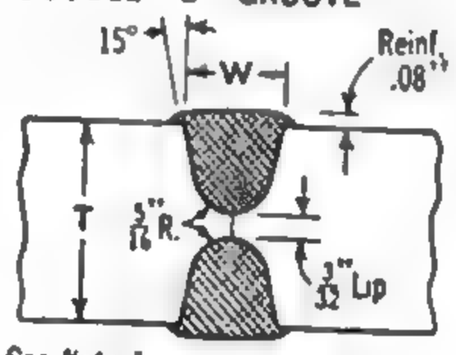
¼	.42	3/32	1.33	.42	.58
5/16	.51	3/32	1.71	.54	.74
3/8	.59	⅛	2.30	.73	1.00
½	.84	⅛	3.85	1.21	1.67
5/8	.91	⅛	4.63	1.46	2.00

"U" GROOVE



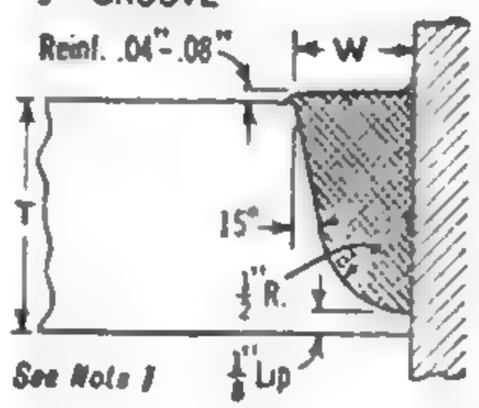
½	.679	....	3.27	1.03	1.41
5/8	.745	....	4.37	1.38	1.90
¾	.813	....	5.33	1.68	2.30
1	.957	....	8.35	2.63	3.60
1¼	1.073	....	11.48	3.62	4.96
1½	1.015	....	15.16	4.79	6.55
1¾	1.349	....	18.90	5.98	8.19
2	1.485	....	23 45	7.40	10.12

DOUBLE "U" GROOVE



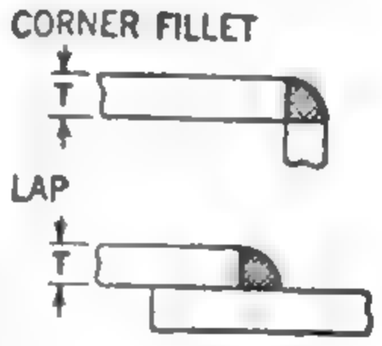
1	.679	....	6.54	2.06	2.82
1¼	.745	....	8.74	2.76	3.80
1½	.813	....	10.66	3.36	4.60
2	.957	....	16.66	5.26	7.20
2½	1.073	....	22.96	7.24	9.92

"J" GROOVE



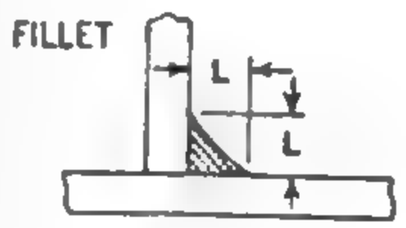
1	.625	....	5.64	1.78	2.4
1¼	.719	....	7.91	2.50	3.4
1½	.781	....	10.20	3.23	4.4
1¾	.875	....	12.95	4.09	5.6
2	.969	....	15.60	4.93	6.8
2¼	1.031	....	18.35	5.80	8.0
2½	1.094	....	21.95	6.94	9.5

CORNER FILLET



1/16	....	....	.05	.03	.04
3/32	....	....	.09	.04	.05
⅛	....	....	.15	.05	.07
3/16	....	....	.33	.10	.14
¼	....	....	.59	.19	.26
5/16	....	....	.92	.29	.40
3/8	....	....	1.32	.42	.57
½	....	....	2.35	.74	1.02

FILLET



...	....	⅛	.09	.03	.04
...	....	3/16	.22	.07	.10
...	....	¼	.38	.19	.26
...	....	5/16	.59	.19	.26
...	....	3/8	.84	.27	.37
...	....	½	1.50	.47	.64
...	....	5/8	2.34	.74	1.01
...	....	¾	3.38	1.07	1 46
...	....	1	6.00	1.90	2.60

NOTE 1–If underside of first bead is chipped out, and welded, add 0.21 lb. of metal deposited (equivalent to 0.29 lb. of electrode).
2–To find linear feet of weld per pound of electrode, take reciprocal of pounds per linear foot.

recommended, as the cuts made are poor and the adjacent area is badly oxidized.

Jigging.—Proper jigging facilitates any welding operation, particularly by minimizing buckling. This is true not only for nonferrous alloys of high melting point but for steels as well.

Backing bars in jigs for arc welding are designed with a rounded groove to assure complete penetration. Grooves should be extremely shallow, usually $^1/_{64}$ to $^1/_{32}$ in. max. depth, and $^3/_{16}$ to $^1/_4$ in. wide. A groove having a rounded contour is preferable to a square one.

Hold-down bars should be of a size and material suitable for controlling distortion and heat dissipation. Commonly used materials are copper, steel and cast iron. Pressure is applied by cams, clamps or hydraulic devices.

Finishing and Cleaning.—The slag is removed from arc welds with hand tools, or with powered wire brushes. It is very important that all flux or slag be removed from the welds if the fabricated part is to be stress, relieved, age hardened or used in high temperature service. Some constituents of the flux will attack the base material at elevated temperatures. This is particularly true if the elevated temperature is above the melting point of the flux. The recommended welding fluxes are not corrosive at room temperature. However, it is usual to remove them as a matter of cleanliness.

The weld reinforcement may be ground off or left on.

Additional information on processing of these materials such as grinding, pickling, etc., which may be necessary after welding, can be found in publications of The International Nickel Co.

Heat Effect of Welding.—There is no detrimental effect on the base metal from the heat of arc welding. The only possible effect is annealing and a very slight grain growth in a narrow band at the edges of the weld, referred to as the heat-affected zone. Strength and ductility of the base metal are not altered noticeably.

Shielded Metal-Arc Welding

Practices in joint design, layout and welding techniques similar to those used in making quality welds in steel are followed in shielded metal-arc welding nickel and high-nickel alloys.

Nickel and Monel can be welded in all positions with the same facility as steel. While Inconel can be welded in any position, it is best, when possible, to position the work for downhand or flat welding.

In general, the lower limit of thickness of sheet for metal-arc welding is 0.037 in. for those structures that can be jigged and 0.062 in. for welding without backing or jigging.

Electrodes.—In general, welding electrodes of the same nominal composition as the base material should be selected. If an age-hardenable base material like Duranickel, "K" Monel or Inconel "X" is welded with a non-hardenable electrode, the resulting weld will not respond to heat treatment. In any event, the weld will produce mechanical properties of annealed material because it is not possible to obtain the benefits of cold work in the region of the weld.

A guide to the selection of proper electrode size is given in Table 7. Electrodes should be kept in a dry place and left in sealed bundles until they are to be used. (See Chapter 38 for further information on electrodes.)

Table 7—Electrode Diameter vs. Sheet Thickness for Shielded Metal-Arc Welding

Electrode Diam., In.	Sheet Thickness on Which Electrode Is Used, In.
$^5/_{64}$	Up to and including 0.062
$^3/_{32}$	Over 0.062 to 0.093
$^1/_8$	Over 0.093 to 0.156
$^5/_{32}$	0.156 and thicker
$^3/_{16}$	0.375 and thicker, and for overlaying
$^1/_4$	Used for overlaying

Mechanical Properties of Welds.—Tensile properties of arc-welded joints in nickel, Monel, "K" Monel, Inconel and Inconel "X" are listed in Table 8. All welds were machined flush with the plate before testing. The values shown in Table 8 for the flat position are equally applicable to the horizontal position.

Preheating.—In general, preheating is neither required nor recommended for arc welding wrought nickel and its alloys. but if the metal temperature should drop to 32°F. or lower, the joint area should be preheated to 70°F. or over for a width of 6 in. on each side of the joint.

Electrode Manipulation.—For welding in the flat and horizontal position, the best electrode position is at an incline of about 20 deg. from the vertical and ahead of

Table 8—Tensile Properties of Welded Butt Joints in Nickel, Monel, "K" Monel and Inconel

Plate Thickness, In.	Type of Groove	Electrode Diam., In.	Average Tensile Strength, Psi — Full Section (Long Gage) — Flat Position	Vertical Position	Overhead Position	— Reduced Section (Short Gage) — Flat Position	Vertical Position	Overhead Position	Minimum Elongation, (Free Bend), %
					Nickel				
1/8	Square	1/8	69,900			71,400	....	....	25
5/16	Single vee	1/8	69,100	.	.	71,200	.. .	....	25
3/8	Single vee	5/32	69,400	.	....	74,000	. .	....	25
11/16	Single vee	5/32	. .	.		77,400	...	.. .	25
					Monel				
1/8	Square	5/32	75,500	76,500	76,600	78,600	78,800	77,800	30
5/16	Single vee	1/8	77,300	76,900	76,300	78,100	79,600	79,100	30
3/8	Single vee	5/32	78,400	80,200	79,800	81,700	83,200	82,100	30
7/16	Single vee	5/32	77,200	.	....	79,800	. .	.. .	30
3/4	Double vee	5/32	. .	.	. .	84,400	. .	....	30
					"K" Monel				
			As-Welded			Age-Hardened[a,b]			As-Welded[a] / Age-Hardened[a,b]
1/8	Square	5/32	89,100	. .	.	129,900	....	...	46 / 19
1/4	Single vee	5/32	90,900	....	....	123,700	....	.. .	51 / 18
3/8	Single vee	5/32	95,500	....	.. .	121,400	...	....	40 / 4
					Inconel				
1/8	Square	5/32	95,700			106,200	....	....	30
3/8	Single vee	5/32	92,400	....	....	93,700	....	....	30
5/8	U Groove	1/8 and 5/32	....	...	....	81,500	....	....	28[a]
					Inconel "X"				
						As-Welded[a]	Age Only[a,b]	Quench[c] and Age[a,b]	As-Welded[a] / Age Only[a,b] / Quench[c] and Age[a,b]
1/8	Single U	5/32	....	....	....	106,000 99,500	167,200 169,000	161,000	27 / 24 / 25

[a] Actual values.
[b] Aging Treatment: "K" Monel; 1100°F., 16 hr., air cool.
Inconel "X"; 1300°F., 6 hr., air cool.
[c] 2000° F., 6 hr., water quench.

the puddle, as shown in Table 5, Column 10. This position is best suited for control of the molten flux and elimination of slag trapping. It is essential that a short arc be maintained.

For overhead welding, the only changes necessary are a slight further shortening of the arc and lowering of the current by 5 to 15 amperes.

For welding in the vertical position the current must be lowered slightly from that used in flat and horizontal welding. For metal 0.062- to 0.109-in. thick, welding should be started at the top and progress vertically downward. On metal thicker than 0.109 in., welding can be either vertially upward or vertically downward. The electrode should be held approximately at right angles to the plate being welded.

Since nickel and high-nickel alloy weld metal is more viscous than steel weld metal, more careful manipulation is necessary to obtain a satisfactory weld contour. The width of a weave should never exceed three times the core wire diameter. Wider beads can result in excessive puddling of the molten weld metal and increase the probability of breaking the protective gaseous shield around the arc, thereby exposing the molten metal to the ambient atmosphere. String beads can be used for work in close quarters where the design or location of the joint prevents weaving.

Arc blow is seldom encountered and there is little or no spatter with high-nickel electrodes, unless excessive current, a long arc or the wrong polarity (with d.c. electrodes) is used. (See Chapter 10 for further information on shielded metal-arc welding.)

Atomic Hydrogen Welding

Atomic hydrogen welding has been used extensively in the automatic production of welded nickel and high-nickel alloy tubing of up to 0.078-in. wall thickness. Uniform penetration is obtained, with sufficiently flat inner and outer weld faces to permit redrawing of the tubing to smaller diameters; no filler metal is added. Manual atomic hydrogen welding may be preferable where absence of porosity is important and where elimination of post-cleaning offers advantages over shielded metal arc and oxy-acetylene welding. (See Chapter 11 for further information on atomic hydrogen welding.)

Inert-Gas Metal-Arc Welding

Inert-gas metal-arc welding is well suited to the welding of Inconel using d.c. straight polarity and either helium or argon as the shielding gas. Extensive use is made of this process in the automatic welding of tubing used as sheathing for electrical resistance heating elements, and in the manual welding of equipment fabricated of thin gage (0.025 to 0.062 in.) Inconel.

Nickel and Monel can be welded by this process using helium of 99.5+% purity. The resulting weld may contain microscopic porosity which will not affect the leak tightness, mechanical properties or corrosion resistance of the weld. If less pure helium is used, major porosity will result. Argon may be employed for welding nickel and Monel if the welding is done with automatic equipment and close control of arc length is maintained. Where the arc length varies, as with manual welding, major porosity may result. The surface condition in each case will be good and radiographing or sectioning must be employed to determine the extent of porosity. Special welding rods are available for use with this process. (See Chapter 12 for further information on inert-gas metal-arc welding.)

Submerged Arc Welding

Nickel and Monel have been welded successfully by submerged arc welding using essentially the same procedures as are used with similar thicknesses of steel. Tests of joints in both nickel and Monel have shown that satisfactory tensile strength, ductility and impact properties are obtained in the welded joints. Tests of the fatigue strength of welds in both nickel and Monel plates have given high values comparable to the fatigue strength of the base metals.

The average mechanical properties of test welds made in $^1/_8$-in. plates in a single pass at a speed of 18 in. per min. for Monel, and at a slightly lower speed for nickel, are given in Table 9.

It is essential that clean flux be used. Flux previously used on stainless or mild steel cannot be used for nickel, Monel or Inconel; if it is used, then unsound welds with low mechanical properties can be expected. (See Chapter 13 for further information on submerged arc welding.)

Carbon-Arc Welding

Carbon-arc welding can be used on nickel and the high-nickel alloys with excellent results; however, the use of this process has practically ceased since the development of improved shielded metal-arc welding electrodes and the atomic-hydrogen and the inert-gas metal-arc welding processes. (See Chapter 9 for further information on carbon-arc welding.)

Stud Welding

Stud welding is applicable to the joining of nickel, Monel and Inconel studs to structures of the same material. These studs can also be joined to many dissimilar metals and alloys. (See Chapter 14 for further information on stud welding.)

Welding Rods.—The available welding rods are of the same nominal composition as the alloy being welded. This is necessary to insure uniform corrosion resistance without galvanic effects. Recommended rod sizes for welding various sheet thicknesses are shown in Table 11 (refer also to Chapter 38).

Flame.—A slightly reducing flame is recommended. Many oxygen and acetylene regulators allow a slight pressure fluctuation; the amount of excess acetylene in the welding flame should be only enough to counteract this fluctuation and prevent the flame from becoming oxidizing in nature.

Fluxes.—Fluxes are required for Monel and Inconel but not for nickel. Borax is not recommended as a flux, because it embrittles the welds. The flux protects the metal from oxidation, dissolves oxides and improves the fluidity of the molten metal. It is used preferably as a thin paste, mixing the dry flux in water for Monel, and with a thin shellac-alcohol solution (in the ratio of 1 to 5) for Inconel. The flux is applied with a small brush or acid swab, on both sides of the seam, top and bottom, and also on the welding rod.

For welding "K" Monel, a flux composed of two parts of boron-free flux (Inconel type) to one part lithium fluoride should be prepared and used as described above for Monel.

Joint Design.—Corner and lap joints may be used where high stresses are not to be encountered. In equipment such as pressure vessels, butt joints are preferred over lap joints.

For butt joints in material of 0.050 to 0.125-in. thick, beveling is not required.

Table 9—Mechanical Properties of Submerged-Arc Welds in 1/2-In. Plate

Material	Yield Strength (0.20%) Offset, Psi.	Tensile Strength, Psi.	Elongation in 2 In., %	Reduction of Area, %	Charpy Impact Strength, Ft.-Lb.
Nickel[a]					
All-weld metal specimens	16,800	55,200	33.0	44.0	56
Reduced section transverse weld specimens	28,000	55,600	21.0	..	..
Monel[b]					
All-weld metal specimens	26,600	62,400	46.0	59.0	42
Reduced section transverse weld specimens	36,900	70,300	45.0	..	..

[a] Fatigue strength (10,000,000 reversals at 6000 rpm. in Krouse test), 29,500 psi. Elongation in free bend, 45%.

[b] Fatigue strength (10,000,000 reversals at 6000 rpm in Krouse test), 31,000 psi. Elongation in free bend, 50%.

Oxy-acetylene Welding

Oxy-acetylene welding is being used in the fabrication of all types of equipment in the many fields in which the high-nickel materials are used. Good welds are produced in all positions.

Mechanical Properties of Welds.—Tensile strengths of oxy-acetylene-welded joints in nickel, Monel and Inconel are listed in Table 10.

Oxy-acetylene welding of Duranickel and "K" Monel is practicable, but is not recommended for Inconel "X" because of the refractory oxides formed during welding.

"K" Monel welds will respond to heat treatment in the same manner as cast "K" Monel. Ranges of hardness of 20 to 30 Rockwell C can be obtained by heat treatment after welding.

In thicker metal, a bevel angle of 37½ deg. (70-deg. groove angle) should be used.

For sheet 0.043 in. and thinner, both butt and corner joints are used. Corner joints can be welded in thicknesses of 0.037 in. and heavier.

Welding Technique.—Usually the same size tips or one size larger than those recommended by the torch manufacturers for similar thicknesses of steel may be used (see Chapter 5). The tip should be large enough to permit the use of a soft flame; a high-velocity or harsh flame is highly undesirable.

Table 10—Tensile Strength of Oxy-Acetylene Welded Joints

Material	Tensile Strength, Min., Psi.
Nickel	60,000
Monel	65,000
Inconel	75,000

During welding, the end of the welding rod always should be kept well within the protecting flame envelope; this prevents oxidation of the heated rod. The tip of the luminous cone of the flame should contact the surface of the pool of molten metal in order to obtain a concentrated heat and to prevent oxidation. Monel and Inconel flow freely from the welding rod into the joint; nickel is a little sluggish. Welds in nickel, Monel or Inconel, either unfinished or ground and polished, are free from porosity.

Preheat.—No preheating is needed for oxy-acetylene welding wrought nickel, Monel or Inconel.

Heat Effect of Welding.—As with arc welding, there is no detrimental effect on the base metal from the heat of oxy-acetylene welding.

Cleaning and Finishing.—Oxy-acetylene welds usually need no finishing except removal of the flux on Monel and Inconel. Removal of flux from units intended for high temperature service is particularly important, since the flux will attack the base metal if the temperature of operation is near or above the melting point of the flux.

Brazing

Nickel and high-nickel alloys may be brazed with the same facility as other common materials. (Refer to Chapter 22 for fundamentals of the various brazing processes.)

Before selecting a brazing alloy it is well to ascertain whether the service requirements of the joint (strength or corrosion resistance) can be obtained using a given brazing alloy. Brazing alloys containing phosphorus should never be used on nickel and nickel alloys. Silver brazing alloys are by far the most frequently used, and the lower melting point alloys are preferred. Copper may be used as a brazing alloy on nickel and nickel alloys.

Fluxes satisfactory for other base materials will be satisfactory for nickel, Monel and Inconel. Special fluxes may be employed for the aluminum-containing materials such as Duranickel, "K" Monel and Inconel "X." If a suitably dry, reducing, sulfur-free atmosphere is available, no flux need be used for furnace brazing with silver or copper brazing alloys. Chromium-containing alloys such as Inconel are frequently copper plated before assembly, when they are to be brazed with copper. This prevents the formation of chromium oxides which will not reduce in the reducing atmosphere of the furnace.

Table 11—Gas-Welding Rod Diameter vs. Sheet Thicknesses

Sheet Thickness, In.	Diam. of Rod, In.	Ft. of Welded Seam per Lb. of Welding Rod
0.031–0.062	1/16	85
0.078–0.109	3/32	42
0.125–0.140	1/8	21
0.156–0.187	5/32	12
0.187 and up	3/16	..

The high-nickel alloys, particularly Monel, are subject to stress cracking in the presence of molten low-melting-point brazing alloys such as those containing cadmium, zinc and silver. Severely cold-worked parts should be annealed before brazing, and the parts should not be subjected to stress during the brazing operation.

Brazing with the low-melting-point silver alloys is carried out below the annealing temperature, and only slight softening is encountered in the base metal. Duranickel and "K" Monel can be age hardened

either before or after brazing with a low-melting-point, silver-containing, brazing alloy.

Brazing materials, particularly copper, diffuse more readily into nickel and nickel alloys than they do into steel. Therefore, a larger reservoir of brazing material is needed for nickel and nickel alloys than for steel and it will not flow as far in a given joint opening. Excess copper may flow during brazing and will perforate thin sections as a result of erosion and diffusion. Sufficient, but not too much, brazing material should be used.

Braze Welding

The usefulness of bronze welding rods for braze welding nickel, Monel and Inconel is very limited because the corrosion resistance of bronze joints frequently is not of the same order as that of the metals being joined. In general, bronze welding rods are useful only for fastenings where corrosive media will not come in contact with the joint.

Braze welding is used in joining nickel-clad steel or Monel to copper varnish kettles.

Soft Soldering

Soft soldering as a means for joining nickel and the high-nickel materials is limited to those applications where the solder is not corroded readily. Soft solder is inherently weak, and dependence for strength must be placed on mechanical joints, such as riveted, lock-seamed or spot-welded joints, with the soft solder acting only as a sealing medium. The process is limited usually to joints in sheet metal not more than 0.062-in. thick because other processes yield stronger joints in these and heavier gages.

Heat treatment of Duranickel and "K" Monel should be done before soldering. Tin-lead solders of the 50–50 and the 60–40 compositions are used most widely. The 60–40 rather than the 63–37 (eutectic) composition is usually preferred. Pure tin is used only where corrosion conditions demand its application.

Preparation of the joints and the procedure to be followed when soldering nickel, Monel and Inconel are the same as discussed in Chapter 23. The major exception is that only those soft-soldering fluxes known in the trade as *acid fluxes* are recommended. Rosin is not suitable since its cleaning action is too mild. The proprietary or *cut acid fluxes* commonly used for copper are adequate for the soft soldering of nickel and Monel, but a somewhat stronger proprietary flux is required with Inconel because of its chromium oxide film.

All traces of flux should be removed after the soldering operation has been completed.

When the heat for soldering is to be supplied by a soldering iron, it is necessary to use either a hotter or larger iron than that regularly used for similar work with copper or steel.

Spot Welding

The fundamental principles of spot welding and the *Recommended Practices for Spot Welding Nickel, Monel and Inconel* are discussed in Chapter 16.

Nickel and the high-nickel alloys are easily spot welded to themselves or to other materials with the proper procedure. The electrical resistivity varies from a low for that of nickel to a high for that of Inconel "X" (see Table 3). The higher resistance materials are more easily spot welded.

The following factors are somewhat different for spot welding nickel alloys than for spot welding other materials.

Cleanliness.—Since the nickel alloys are susceptible to sulfur embrittlement at elevated temperatures, all sulfur-containing materials such as grease, oil, drawing compounds and marking paints should be removed from the surface before welding. The presence of surface oxides is as injurious with nickel alloys as it is with many other metals.

Electrodes.—RWMA Class 2 electrodes are recommended generally. On very thin material, there will be less sticking with Class 1 or hard-rolled copper electrodes. Flat-faced electrodes with a bevel of 20 deg. from the face are recommended for Monel and Inconel, while a 10-deg. bevel minimizes sticking with nickel. Domed electrodes require more pressure and longer firing times to prevent cracking.

Pressure.—Unit pressures of the order of 20,000 to 40,000 psi. are required to permit adequate forging in these alloys.

Inspection.—Sectioning and etching the weld are recommended over peel testing (prying two welded sheets apart and peeling one sheet back over the other). The peel test will not distinguish between a

weld in these alloys with adequate penetration, and one that is just barely fused.

Seam Welding

Specific seam welding data are not available yet for nickel and the high-nickel alloys. Nevertheless the information in Chapter 16 on *Recommended Practice for Seam Welding Stainless Steel* may be used as a guide.

Projection Welding

Specific data for projection welding nickel and high-nickel alloys are not available. Generally higher forging pressures and longer firing times are required, than for steels.

Table 12—Recommended Conditions for Cross-Wire Welding of Nickel, Monel and Inconel

Wire Diam., In.	Electrode Pressure, Lb.	Firing Time, Cycles	Current, Amp.
	Nickel		
1/16–1/16	90	2	2000
1/8–1/8	180	3	4500
3/16–3/16	360	6	7000
1/16–1/8	90	2	2200
1/16–3/16	90	2	2400
1/8 –3/16	180	6	5000
	Monel		
1/16–1/16	100	2	1630
1/8–1/8	200	3	3700
3/16–3/16	400	6	5700
1/16 1/8	100	2	1790
1/16–3/16	100	2	1950
1/8 –3/16	200	3	4050
	Inconel		
1/16–1/16	125	2	1050
1/8 –1/8	250	3	2300
3/16–3/16	500	6	3600
1/16–1/8	125	2	1100
1/16–3/16	125	2	1200
1/8 –3/16	250	3	2500

Cross-wire welds in nickel, Monel and Inconel are a special type of projection welding. Table 12 gives the recommended procedures.

Flash Welding

Nickel and the high-nickel alloys can be flash welded to themselves or to many other metals. Table 13 gives recommended schedules for 1/4- and 3/8-in. diam. bars in nickel, Monel, "K" Monel and Inconel.

Since the alloys have higher strength than steel at elevated temperatures, more pressure is required to forge and extrude all cast material from the joint. The time of current flow during upset is rather critical; if too long, there is a chance of overheating and burning the material; if too short, the plasticity of the material is not great enough to allow extrusion of cast material during forging.

Pressure Gas Welding

Pressure gas welding can be used for joining rod, bar or pipe forms in nickel and high-nickel alloys. (Pertinent details concerning this process will be found in Chapter 7.)

Machine settings and mechanical properties of 0.505-in. tensile specimens of welds are shown in Table 14.

Gas and Arc Cutting

Nickel and the high-nickel alloys cannot be cut by the conventional oxygen cutting process. They can be cut by either of two processes that have been developed for cutting materials other than steel. These are the powder and oxy-arc cutting processes. (Complete descriptions of these processes will be found in Chapters 24 and 25.)

The data contained in Table 15 have been assembled from various sources and may be used as a guide in determining operating conditions for powder cutting. All the data were obtained from cuts made on pantograph machines. The extent to which the speeds will be reduced in manual cutting will depend upon the shape of the piece being cut and the skill of the operator.

Cutting by the oxy-arc process is limited to manual use; therefore, it is not possible to tabulate data on speeds. It is relatively easy to acquire the necessary skill to produce satisfactory cuts in nickel, Monel and Inconel. For instance, cutting speeds of approximately 6 in. per min. can be attained in 1/4-in. plate of all three materials using 150 to 160 amp., and approximately 5 psi. oxygen pressure. The speed of cutting is greatly influenced by the skill of the operator. As the operator becomes acquainted with the process, he learns to manipulate the electrode in such a manner as to increase the speed of cutting. The practical limit of thickness of nickel, Monel and Inconel which can be cut using 3/16-in. diam. electrodes now available is 2 to 3 in., although thicker material may be pierced

Table 13—Recommended Schedules for Flash Welding Nickel and Nickel Alloy Rods

Material	Rod Diam., In.	End Preparation	Flashing Distance, In.	Flashing Time, Sec.	Current Duration During Upset Cycles	Upset Distance, In.	Energy Input, Watt Hr./Weld	Weld Strength, Psi.	Rod Strength, Psi.
Nickel	1/4	Pointed	0.442	2.5	1 1/2	0.125	2.15	58,000	65,100
Nickel	3/8	Pointed	0.442	2.5	2 1/2	0.145	4.87	65,600	66,500
Monel	1/4	Pointed	0.442	2.5	1 1/2	0.125	1.93	68,500	70,500
Monel	3/8	Pointed	0.442	2.5	2 1/2	0.145	5.55	80,300	84,700
"K"									
Monel	1/4	Pointed	0.442	2.5	1 1/2	0.125	2.02	93,900	100,000
"K"									
Monel	3/8	Pointed	0.442	2.5	2 1/2	0.145	4.79	98,800	99,000
Inconel	1/4	Pointed	0.442	2.5	1 1/2	0.125	2.15	101,200	109,800
Inconel	3/8	Pointed	0.442	2.5	2 1/2	0.145	5.19	102,000	106,000

Table 14—Pressure Gas Welding 1-In. Diam. Bars

	Nickel	Monel	"K" Monel	Inconel
Approximate time, min. and sec.	1–30	1–5	2–15	1–15
Oxygen } Flow rate, cu. ft./hr.	41.5	72.0	38.5	54.0
Acetylene }				
Upsetting pressure, psi.	4500	6000	8100	10,800
Shortening, in.	0.5	0.5	0.5	0.5
Heating stroke, in.	0.5	0.5	0.5	0.5
Tensile strength,[a] psi.	64,500	72,250	128,100[b]	96,200
Yield strength[a] (0.2% offset), psi.	16,175	26,000	87,375[b]	36,150
Elongation in 2 in.,[a] %	39.5	35.0	11.5[b]	34.3
Type failure	Cup and cone	Cup and cone	In weld	Cup and cone

[a] From 0.505 all-weld-metal specimen.
[b] Age hardened.

Table 15—Powder Cutting Guide

Material	Thickness, In.	Speed, In./Min.	Powder Consumption, Oz./Min.	Oxygen Pressure, Psi.	Nozzle Diam., In.	Comments
Nickel	1/4	11.0	4.5	40	0.060	Good cut
	15/16	4.5	9.0	65	0.100	Very rough cut
	15/16	4.0	9.0	65	0.100	Moderate rough cut, 500° F. preheat
	5	...	....	75	0.200	Would not cut
Monel	1/4	11.0	4.5	40	0.060	Good cut
	1/2	5.5	5.0–6.0	30	0.060	Good cut
	1	4.6	6.0	65	0.100	Rough cut
	1	4.4	6.0	65	0.100	Moderate rough cut, 500° F. preheat
	5	3.0	12.0	75	0.200	Fairly smooth cut, 700° F. preheat
Inconel	1/4	26.0	4.0–5.0	40	0.060	Good cut
	5/8	7.0	9.0	65	0.080	Fairly smooth

Table 16—Filler Metal for Shielded Metal-Arc Welding of Dissimilar Metals

	Nickel	"L" Nickel	Monel	"K" Monel	Inconel
Nickel	1	1	0, 1	0, 1, 4	1, 2, 3
"L" Nickel	1	1	0, 1	0, 1, 4	1, 2, 3
Monel	0, 1	0, 1	0	0, 4	1, 0, 2
"K" Monel	0, 4, 1	0, 4, 1	0, 4	4	1, 0, 4
Inconel	1, 2, 3	1, 2, 3	1, 0, 2	1, 0, 4	2, 3
Carbon Steel	1, 0, 2	1, 0, 2	2, 5, 1	2, 5, 1	3, 2
Galvanized Steel	1, 0	1, 0	1	1	1
Stainless Steels	2, 1, S	2, 1, S	0, 1	0, 1	2, 3, S

NOTE: Recommendations are in the order of preference.
CODE:
0—Monel electrodes.
1—Nickel electrodes.
2—Inconel electrodes.
3—80/20 nickel-chromium electrodes.
4—"K" Monel electrodes.
5—Special Monel electrode.
S—Stainless steel electrodes. (Normally of same type as plate material also stabilized.)

by this process. Simple gouging or forming operations may also be performed.

Burned material and iron oxide adhering to the cut edges must be removed by grinding or machining prior to further fabrication. The heat-affected area is very shallow. If all discolored material is removed, the corrosion resistance of the base material will be unimpaired by either of the above processes.

Nickel, Monel and Inconel cannot be cut satisfactorily by the flux-cutting process developed for cutting stainless steels.

Joining Dissimilar Metals

Welding and soft soldering can be used for joining dissimilar metals. The process selected depends on the conditions to be encountered in service. If a material can be soft soldered or brazed readily, then, other things being equal, it can be joined to nickel, Monel or Inconel.

The most frequently used arc-welded combinations are nickel-to-steel and Monel-to-steel in clad steel fabrication (see Chapter 37A). For both, nickel or special Monel electrodes should be used. In arc welding dissimilar metals, it is essential that penetration be kept to a minimum. Therefore, excessive welding currents and puddling must be avoided.

Combinations that have been metal-arc welded successfully are listed in Table 16 which also shows the proper filler metal to use.

Thermal Treatment

Since the corrosion resistance of nickel, Monel and Inconel is inherent, heat treatment after welding is not necessary for the restoration of corrosion-resisting properties. The heating of welded vessels of nickel, Monel and Inconel for relief of stresses set up because of the welding operation may be called for in special instances, but in general it is not recommended. This is because these materials are highly ductile in both plate and weld metal and, in the range of plate thicknesses normally encountered in vessel construction under $^3/_4$ in., do not require a heat treatment for the reduction of welding stresses.

When a stress-relief heat treatment is specified to fulfill a code requirement, the time and temperature recommended are those used for steel vessels, namely 1100 to 1200°F. for 1 hr. per in. of thickness. Code requirements should be followed in other details also, and particular care should be given to supporting the vessel in all directions so that it will not be distorted during heating.

Special thermal treatment for Hastelloy alloys may be advisable; specific recommendations should be obtained in each instance.

Inspection

Radiographic Examination. — Radiographs of properly welded joints in nickel and high-nickel alloys are acceptable according to the standards set for steel by the ASME Code for Unfired Pressure Vessels.

Etching Solutions for Welds.—Polished sections of welded joints can be etched readily to disclose the weld and base metal structures by immersion for 5 to 10 sec. in the following etchants: for nickel—cold, concentrated nitric acid; for Monel—a cold solution of equal volumes of water and concentrated nitric acid; for Inconel—warm aqua regia (three parts hydrochloric acid, one part nitric acid) after first warming the specimen in hot water. If the Inconel weld does not etch readily, a small amount of cupric chloride may be added.

Surfacing Nickel and High-Nickel Alloys

A number of abrasion-resistant surfacing alloys can be applied readily to nickel, Monel, "K" Monel and Inconel with the aid of the oxy-acetylene welding torch. Colmonoy and the cobalt-chromium-tungsten alloys (Stellites) are materials that have been used for overlays. The Colmonoy alloys are complex mixtures of very hard chromium-boride crystals in a matrix of nickel. Melting points of the Colmonoy alloys are very close to 2000°F. Varying hardnesses are obtained by controlling the proportions of boride crystals and nickel; for example, a composition containing approximately 69% nickel (balance crystals), has a hardness, as deposited, of 45 to 55 Rockwell C. The high nickel contents of the Colmonoy materials make them very useful for resistance to abrasion in corrosive environments.

The cobalt-chromium-tungsten alloys melt at temperatures from 2282 to 2327°F. They have good gas-welding properties

They are available in several grades to meet the requirements of all surfacing applications.

When applying the Stellite and Colmonoy surfacing materials, the base metal temperatures should be only slightly above the melting point of the surfacing material to avoid boiling and formation of holes in the overlay.

Both the Stellite and Colmonoy alloys can be applied to nickel and Monel without flux, but a flux, active at 1800 to 2000°F., is required for facing "K" Monel and Inconel. The flame should be neutral to slightly reducing for the Colmonoy alloys and highly reducing for the Stellite alloys.

Surfacing Nickel and High-Nickel Alloys on Cast Steel and Wrought Steel.—Nickel, Monel, "K" Monel and Inconel can be applied on cast and wrought steel readily by shielded metal-arc welding. Certain precautions must be observed to obtain sound, crack-free deposits. The surface to be overlaid must be cleaned to remove all oil, grease, oxide or other foreign matter.

The selection of the electrode diameter for the first layer must be based upon the amount of iron dilution permissible in the overlay. If the overlay is to be three or more layers deep, then dilution in the first nonferrous layer is not too important as the iron content will decrease with each successive layer. Minimum iron content will be obtained in the third or fourth layer.

The first layer can be applied either as a *wash bead* laid down with a fairly fast weave or by using a slightly lower current density and traveling at a relatively slow rate so that the arc is always on a heavy puddle of weld metal. Either technique minimizes penetration into the base metal. The second and succeeding layers may then be applied using $^{5}/_{32}$- to $^{1}/_{4}$-in. diam. electrodes, the size of the electrode depending upon the thickness of base metal and the area which must be covered. It is important that the slag be removed from each bead before applying the next one.

Monel and "K" Monel overlays applied directly to the base metal may contain small checks or cracks. When the service conditions are such that crack-free overlays must be obtained, it is recommended that the first layer be applied with pure nickel electrodes. This will provide a barrier layer on which the Monel and "K" Monel may be applied. Nickel and Inconel can be applied directly to clean, cast or wrought steels. A special Monel electrode is also available for overlaying directly on steel without cracking. (See Table 17).

Sound overlays require the complete removal of slag from each bead before starting the next bead or layer. The beads can be applied in any direction, but it is suggested that they be applied in the long direction of the overlay. Better control of contour is obtained by applying narrow string beads rather than wide, weave beads. Each string should overlap the previous one by approximately 50%. Peening of nickel and high-nickel alloy overlays is not necessary.

Table 17—Surfacing of Steel and Cast Iron

Overlay Material	Electrode Diam. (In.) and Current (Amp.) $^{1}/_{8}$ In.	$^{5}/_{32}$ In.	$^{3}/_{16}$ In.	$^{1}/_{4}$ In.	Brinell Hardness
Nickel	100–125	125–170	160–200	.....	155–190
Monel	80–90	125–150	160–190	170–250	150–160
"K" Monel	80–90	125–150	160–190	.....	150–160 (as-welded) 260–280 (heat treated)
Inconel	90–100	125–150	160–190	.....	130

Nickel-Chromium and Nickel-Chromium-Iron Heat-Resisting Alloys

There are a number of nickel-chromium alloys which are used primarily as heat-resisting alloys in such applications as the heat treatment of steel, carburizing, enameling, glassmaking and other high-temperature applications.

Only those alloys containing 50% or more nickel are discussed in this chapter, namely:

(*a*) 65 to 68% nickel and 15 to 19% chromium.

(*b*) 59 to 62% nickel and 10 to 14% chromium.

(*c*) 80% nickel and 12 to 20% chromium.

These materials, both in cast and rolled forms, are known by many trade names some of which are listed on page 774.

They are non-carburizing and have a characteristic non-flaking scale.

Wrought material is joined by oxy-acetylene, shielded metal arc or atomic-hydrogen welding. Since the materials are furnished usually in hot-rolled form, a thin, dark-colored oxide covers them. Good welding practice requires that the oxide film be removed from the immediate vicinity of the area to be welded either mechanically by machining, sandblasting, grinding or rubbing with coarse emery cloth, or chemically, by pickling. Light grinding, with either fine-grit solid emery wheels, emery discs or rolled-head wheels, is employed most frequently. Difficulty in the form of an unstable arc in arc welding, and difficulty in melting through the oxide film in flame welding, is encountered if the oxide is not removed.

In oxy-acetylene welding, the use of a flux is not mandatory, but it is beneficial in keeping the chromium oxide from forming and being a disturbing element. The flame should be very slightly reducing. Welding rods, either drawn or cast, but of the same general composition as the metal being welded, are used as filler metal. The surface of cast welding rods should be free from molding sands and other foreign materials.

Covered welding electrodes are made in the same general compositions as the wrought materials. All are used with d.c. reversed polarity (electrode positive).

In joining these materials, practices for fit-up and welding employed for high-quality fabrication of steel are used without important change. Since the coefficients of expansion of the alloys containing 59 to 68% nickel are appreciably higher than that of steel, expansion and contraction must be taken into account if excess buckling is to be avoided. The heat-resisting alloys containing approximately 80% of nickel have coefficients of expansion approximately the same as that of steel.

Hastelloy Alloys

With a few exceptions the techniques established for joining austenitic stainless steels may be used for welding Hastelloy alloys. As with stainless steels, proper care must be taken to prevent distortion and undesirable heat effects. While these alloys are not especially susceptible to carbide precipitation, sufficient care must be taken to confine the heat to minimum areas and to shorten the time at welding heat.

Hastelloy alloys can be welded satisfactorily by the atomic hydrogen or inert-gas metal-arc welding processes. Both a.c. and d.c. are used with the inert-gas process, although d.c., straight polarity is preferred. Manual or machine welding can be used without the aid of flux. The use of argon as a shielding gas is preferred, since it has a greater stabilizing effect on the arc than helium, especially on thin sheet (24 gage).

Shielded metal-arc welding is also a satisfactory method of welding Hastelloy alloys. In general, joint designs established for carbon steel are acceptable for the Hastelloy alloys. Direct current reversed polarity is most generally used. Welding electrodes of the various alloys are available with balanced analyses providing for composition changes during welding. However, in many cases, electrode materials of dissimilar composition may be used for joints to secure stronger welds and lessen notch cracking.

Submerged arc welding may be used also for welding the Hastelloy alloys.

Oxy-acetylene welding, with certain limitations, can be used for welding these alloys; in general, however, the faster and carbonless arc methods are preferred. The chief disadvantage in using the oxy-acetylene process lies in the danger of carbide precipitation caused by holding the metal at too high a temperature for too long a period of time. Then, too, there is always a possibility of carbon absorption in the weld area caused by excess acetylene in the gas mixture. Precipitation and carbon pickup can be controlled, however, through the use of special fluxes and by proper torch operation. When welding with the oxy-acetylene process, best results can be obtained by using a neutral flame and a tip several sizes smaller than is ordinarily used for joining plain steel. An oxidizing flame should never be used.

Illium

The nominal composition, physical and mechanical properties of Illium are shown in Tables 2, 3 and 4, respectively. Illium may be welded by either shielded metal-arc or oxy-acetylene welding.

Coated Illium electrodes are designed for use with d.c., reversed polarity (electrode positive). A short arc should be

maintained. A current of 80 to 90 amp. is recommended for 1/8-in. diam. electrodes.

Weld preparation similar to that employed on other high-nickel alloys is used. Normally, no preheat is necessary; however, on very rigid structures, a preheat of 1400°F. will prevent cracking during cooling. Where possible, the full depth of the joint should be built up in one operation, rather than in layers. Where it is necessary to make the weld in layers, the metal should be allowed to cool and the slag should be cleaned off thoroughly prior to deposition of subsequent passes. Slag inclusions or incompletely fused areas should be ground out before proceeding.

Illium may be welded satisfactorily by the oxy-acetylene welding process using a reducing flame, a tip one size larger than that employed for steel, a welding rod of the same composition as cast Illium G, and a flux similar to that employed for cast iron. The surfaces to be welded should be ground or machined for cleaning and to produce an edge preparation which will permit sufficient manipulation to insure complete penetration Preheating to 1400°F. is advisable.

The base metal should be fluid before adding filler metal, which should be added to the molten pool only. The weld should be puddled to permit oxide, impurities and gases to float out and the flame should be withdrawn slowly to permit gradual solidification from the bottom up It is important to observe that in all welding where the complete area cannot be covered by the flame of the torch, the metal should be applied so that the torch tip is pointing toward the completed weld at an angle of 45 degrees.

COMMON APPLICATIONS

Nickel and the high-nickel alloys are used as materials of construction where their special properties will give them an economic advantage over other materials. The selection of a nickel alloy will generally be decided on the following requirements or properties:

1. Resistance to corrosion by a wide variety of corrosive media and over a wide range of temperatures.
2. Purity of product.
3. Peculiar physical properties such as magneto-striction, emissivity, spring properties at elevated temperatures and others.

The fields of application are numerous. A few examples will serve to illustrate current usage and to suggest others.

Nickel—Food-processing vessels; chemical reaction vessels; caustic evaporators; tank cars and shipping containers; heat exchangers; pipe lines and valves; instrument parts; electronic tube parts; gaskets.
"L" Nickel—Caustic manufacturing equipment.
Duranickel—Springs; plastic extrusion dies.
Inconel "X"—Gas turbine rotors and blades; bolts; springs.
Inconel—Aircraft manifolds and heaters; leather tanning drums; furnace fixtures and parts; chemical processing equipment.
Other Nickel-Chromium Alloys—Heating elements; heat-treating equipment.
Monel—Chemical processing equipment; petroleum reaction vessels; pulp and paper mill equipment; pickling chains and crates; locomotive staybolts; kitchen utensils, sinks, pot cleaners; laundry equipment; pipe-line valves; heat exchangers.
"K" Monel and "KR" Monel—Aircraft instruments; propeller shafting; springs; oil well drill collars.
"R" Monel—Screw machine parts.
Hastelloys and Illium—Chemical-processing equipment; acid-processing equipment.

BIBLIOGRAPHY

1. *The Spot Welding of Nickel, Monel and Inconel*, W. F. Hess and A. Muller, The Welding Journal Res. Suppl., October 1941.
2. *The Flash Welding of Nickel and High-Nickel Alloy Rod*, W. F. Hess and A. Muller, The Welding Journal Res. Suppl., October 1943.
3. *Pressure Vessels Made with Welded Nickel Alloy Linings*, T. H. Menaugh, Materials and Methods, May 1946.
4. *Welding and Other Fabrication Methods for Hastelloy Alloys*, C. G. Chisholm, The Welding Journal, December 1946.
5. *Joining Corrosion-Resistant Alloys by Submerged Arc Welding*, R. J. Anderson and H. J. Roberts, The Welding Journal, April 1947 (also Materials and Methods, July 1947).
6. *Welding and Fabrication of High-Temperature Alloys*, C. G. Chisholm, The Welding Journal, March 1948.
7. *Welding, Brazing and Soft Soldering of Monel, Nickel and Inconel*, Technical Bulletin T-2, International Nickel Co., 1948.
8. *Haynes Alloys for High-Temperature Service*, Form 8612, Haynes Stellite Co.
9. *Hastelloy High-Strength, Nickel-Base, Corrosion-Resistant Alloys*, Form 3361E, Haynes Stellite Co.

CHAPTER 36

LEAD AND ZINC*

A. LEAD

INTRODUCTION

THE WELDING OF lead is similar to the welding of other metals, the purpose being to join two separate sections of metal into one continuous piece. However, the technique used to bring about this desired result differs considerably between lead and other metals. An important difference in gas welding lead to lead is that no flux is required. In the past the common term for lead welding has been *lead burning*. Since the result of the operation is a true weld this is a misnomer.

Probably the first successful attempt at welding was done on lead. This has been shown by samples of lead pipe dating back over 1800 years. The Romans of that era had complete water distribution systems and most of the pipe used to convey the water within the cities and homes was lead. The pipe was manufactured in standard lengths and sizes and the method of manufacture was a crude form of welding as compared to methods of today.

GENERAL PROPERTIES

As a raw material lead is marketed in pigs averaging 100 pounds. Pig lead is available in several grades as specified in the ASTM *Standard Specifications for Pig Lead* (Serial Designation: B29-43). (See Table 1).

The various grades of lead find their principal use in certain applications but are not necessarily confined to those applications. For example, corroding lead, because of its high purity, is most extensively employed in the manufacture of white lead and other pigments. Chemical lead, acid lead and copper lead are widely used under corrosive conditions. Common desilverized lead A, common de-

Table 1—Chemical Composition of Pig Lead

	Corroding Lead*	Chemical Lead*	Acid Lead*	Copper Lead*	Common Desilverized Lead A*	Common Desilverized Lead B*	Soft Undesilverized Lead*
Silver, max., per cent	0.0015	0.020	0.002	0.020	0.002	0.002	0.002
Silver, min., per cent	....	0.002	....	....	....	....	....
Copper, max., per cent	0.0015	0.080	0.080	0.080	0.0025	0.0025	0.04
Copper, min., per cent	....	0.040	0.040	0.040	....	....	....
Silver and copper together, max., per cent	0.0025	....	....	....	....	....	....
Arsenic, max., per cent	0.0015	....	....	....	....	....	....
Antimony and tin together, max., per cent	0.0095	....	....	....	....	....	....
Arsenic, antimony, and tin together, max., per cent	....	0.002	0.002	0.015	0.015	0.015	0.015
Zinc, max., per cent	0.0015	0.001	0.001	0.002	0.002	0.002	0.002
Iron, max., per cent	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Bismuth, max., per cent	0.05	0.005	0.025	0.10	0.15	0.25	0.005
Lead (by difference), min., per cent	99.94	99.90	99.90	99.85	99.85	99.73	99.93

* Explanatory Note:
Corroding lead is a designation that has been used for many years in the trade to describe lead which has been refined to a high degree of purity.
Chemical lead has been used for many years in the trade to describe the undesilverized lead produced from Southeastern Missouri ores.
Acid lead is made by adding copper to fully refined lead.
Copper lead is made by adding copper to fully refined lead.
Common desilverized leads A and B are designations that are used to describe fully refined desilverized lead.
Soft undesilverized lead is used in the trade to describe the type of lead produced from ores of the Joplin, Mo. district.

* Prepared by a committee consisting of G. O. Hiers, National Lead Co., *Chairman;* D. M. Borcina, Lead Industries Assn.; S. E. Maxon, The New Jersey Zinc Co.; J. H. Torrence, Consulting Engineer.

silverized lead B and soft un-desilverized lead are essentially for general purposes.

Lead is easily rolled into sheets, extruded into pipes and fittings, cable sheathing, and in fact practically any desired cross-section. It is easily worked, forged and cast, and is alloyed with many other metals. Two alloys commonly used in welding are tellurium lead and antimonial lead, in both of which the alloying elements impart certain characteristics to the lead. The addition of tellurium, less than 0.1%, improves the work-hardening capacity of the lead. The addition of antimony, usually about 6%, increases the hardness and provides about twice the tensile strength of soft lead at ordinary temperatures. However, antimony lowers the melting point markedly depending on the percentage used.

Lead melts at 621°F. and boils at 3092°F. When freshly cut, its surface has a bright silvery luster which oxidizes to a dull gray. Lead is resistant to corrosion from ordinary atmosphere, moisture and water and is particularly effective against many acids, such as sulphuric and chromic.

In specifications the thickness of sheet lead is usually referred to by weight in pounds per square foot. The thickness in inches can easily be ascertained by following, in general, the formula 1 sq. ft. of lead $^1/_{64}$-in. thick equals 1 pound. For example, 8 lb. sheet lead weighs 8 lb. per sq. ft. and is $^8/_{64}$ or $^1/_8$-in. thick.

Lead pipe is usually specified by inside diameter and weight per foot or by wall thickness.

HOW TO WELD

Processes Used

Gas welding is most commonly used for welding lead. Other welding processes have been used on an experimental basis only.

Special Tools of the Lead Welding Operator

The following tools are needed by the lead welder:

1. Welding torch tips ranging in drill size from about 78 to 68. The smaller tips are for use with 6 lb. lead and lighter, and the larger tips for heavier lead. Depending upon conditions and the welder's experience, torch tips larger than 68 drill size are sometimes used. Light fingertip torches separated from the control taps and easily accessible to the welder are preferred.
2. Mallets and dressers, of materials that will not dent or mar the lead, for dressing the sections of lead to be joined so that they are suitably aligned for welding.
3. Wooden turn pins for expanding one end of a length of pipe so as to easily insert another section of pipe to form a cup or lap joint.
4. Shave hooks, scrapers and wire brushes for cleaning or removing oxide from the lead over the areas that are to become a part of the joint.
5. Various tools for uniformly cutting the lead.
6. Metal molds for use on vertical butt seams.

Gases Used

There are three combinations of gases commonly used. They are oxy-acetylene, oxy-natural gas and oxy-hydrogen. The oxy-hydrogen mixture can be used for all positions and is considered the most satisfactory fuel. In general, oxy-acetylene is satisfactory for all positions of welding. The oxy-natural gas mixture is satisfactory for the flat, horizontal and vertical positions.

Gas Pressure and Type of Flame

A low gas pressure, from $1^1/_2$ to 5 psi., is generally used varying with the type of weld to be made. The flame must be a neutral one inasmuch as a reducing flame will deposit soot on the joint and an oxidizing flame coats the molten globules of lead with an oxide film which acts as a barrier between the molten globules preventing coalescence. The length of the flame will vary, but is usually somewhere between $1^1/_2$ to 4 in. depending upon the pressure and volume of gas used.

Welding Rods

Filler metal is generally used, in the form of welding rods in sizes from $^1/_8$ to $^3/_4$ in. in diameter. The smaller sizes are used for light-weight lead and the larger sizes for heavier lead. The selection very often depends upon the welder's preference. The welding rods should be of the same composition as the lead to be welded. For example, if 6% antimonial

lead is being welded, then a 6% antimonial lead welding rod should be used.

Working Precautions

The sections of the lead that are to become a part of the joint should be scrupulously cleaned by shaving or wire brushing. This includes the inner surface of pipe joints in contact as well as the exposed areas. On square butt joints the abutting edges as well as the surface on which the reinforcement will be deposited should be cleaned. On lap joints the edge and underside of the lapping sheet and the underlapping sheet extending beyond the lap to the end of the area over which the weld will be deposited should be cleaned.

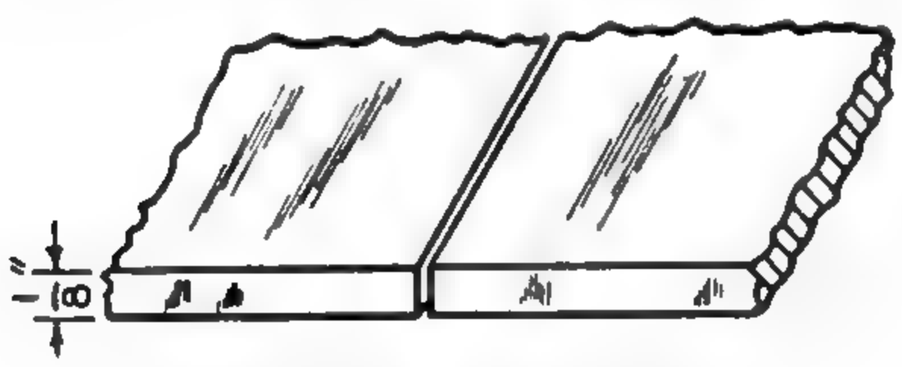


Fig. 1.—Butt Joint for Sheet Lead 1/8 In. Thick or Less

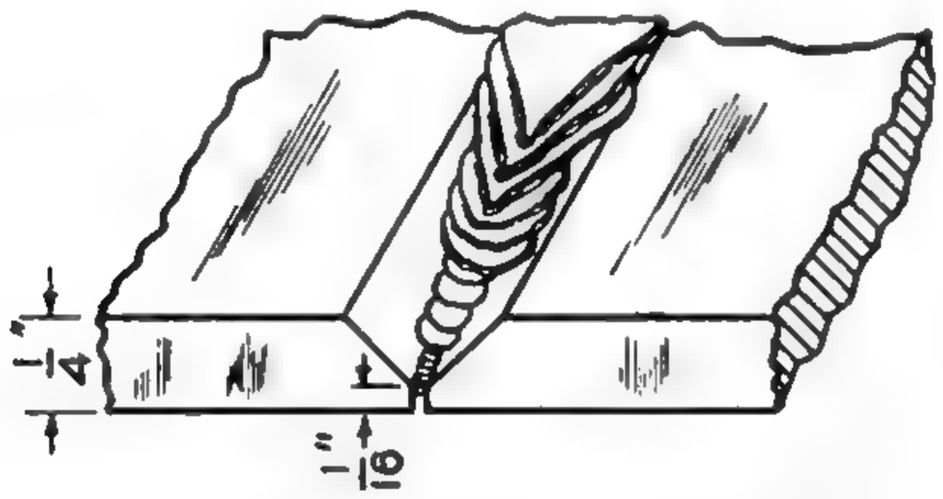


Fig. 2.—Butt Joint for Sheet Lead Over 1/8 In. Thick

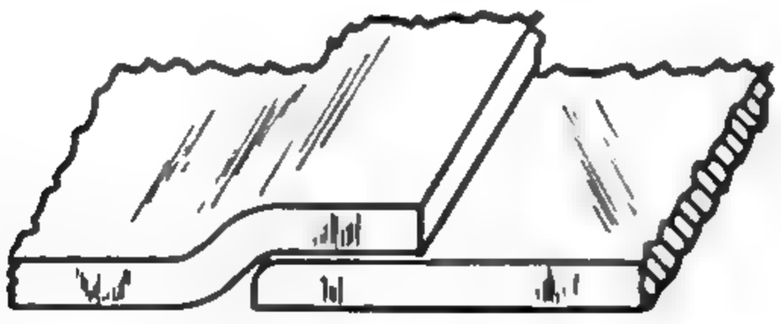


Fig. 3.—Lap Joint in Sheet Lead

Types of Joints

(*a*) *Sheet.*—There are three basic types of joints commonly used in welding lead sheet. These are the butt, lap (see Figs. 1, 2 and 3) and flange types. On flat work the butt and lap types of joint can be used interchangeably depending upon conditions of installation. On vertical and overhead welding, the lap joint is almost always used. The flange joint, which is not illustrated, is used only under special conditions.

(*b*) *Pipe.*—The butt joint is usually preferred, with the lap and cup joints

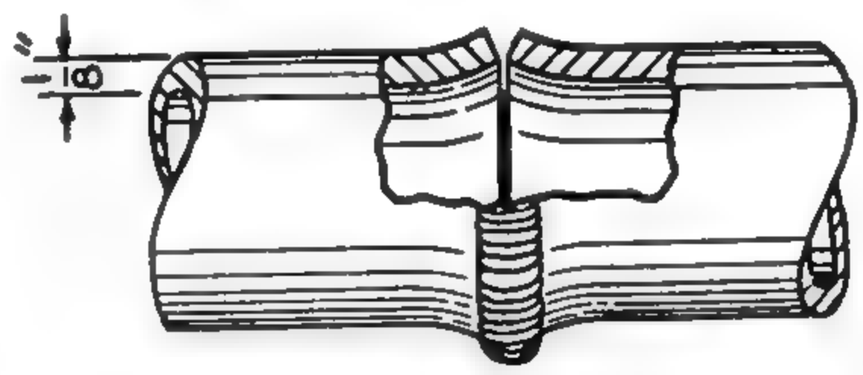


Fig. 4.—Butt Joint for Pipe with 1/8 In. Wall Thickness or Less

as alternatives on lighter weight lead, up to about 5/32-in. thick. (See Figs. 4, 5 and 6.) The flange joint is often used on larger diameter pipe but differs from

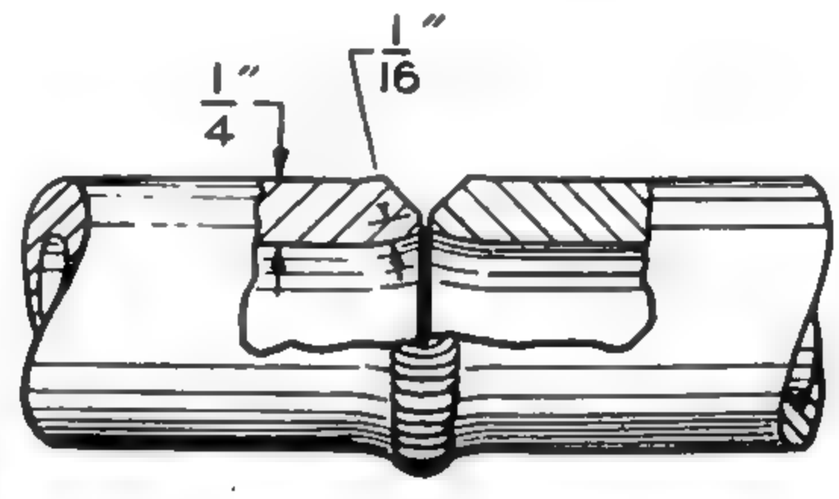


Fig. 5.—Butt Joint for Pipe Over 1/8 In. Wall Thickness

the flange joint in sheet lead. The flange for pipe joints is cast or made from sheet lead and then welded to the pipe.

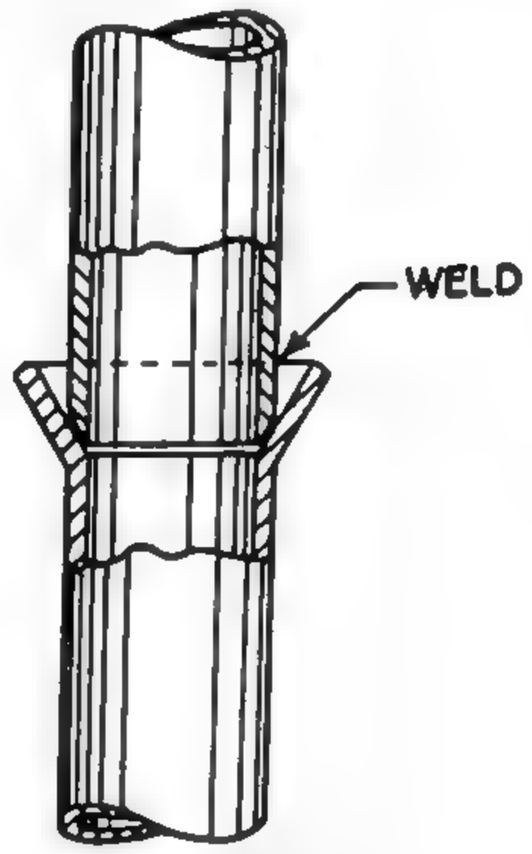


Fig. 6.—Cup Joint for Pipe in Vertical Fixed Position

Preparation for Welding

The lap joint is prepared by lapping the edge of one member over the other about 1/2 to 2 in. depending upon the

thickness of the lead. The thicker the lead the greater should be the lap. The underside, top and edge of the upper member are scraped clean as is the top of the lower member. Cleaning is necessary only over the area that is to become part of the welded joint.

The butt joint is prepared by placing the edges of both members together. For material weighing less than 8 lb. ($^1/_8$-in. thick) no beveling of the edges is necessary. However, for heavier weights the edges should be beveled to an included angle of 45 to 90 deg. except for a root face of $^1/_{16}$ in. minimum, usually without root opening. (See Fig. 2.) The root faces should be shaved clean as well as the top surfaces of the two parts over the area forming the joint.

The flange joint for use with 4 lb. and lighter sheet is prepared by turning up the ends of the sheets to be joined, both sides and edges of the upturn being thoroughly scraped clean and then butted together.

Manipulation of the Torch

Manipulation of the torch and the kind of flame used depend on the type of joint being welded and the position of welding. In general, a semi-circular or V-shaped motion is used. The molten lead is controlled and flowed with the flame, thus accounting for the circular or herringbone appearance of the joint. Each semicircle or Vee is made in one continuous operation, the flame being flicked away from the work at its completion. (See Figs. 2 and 7.)

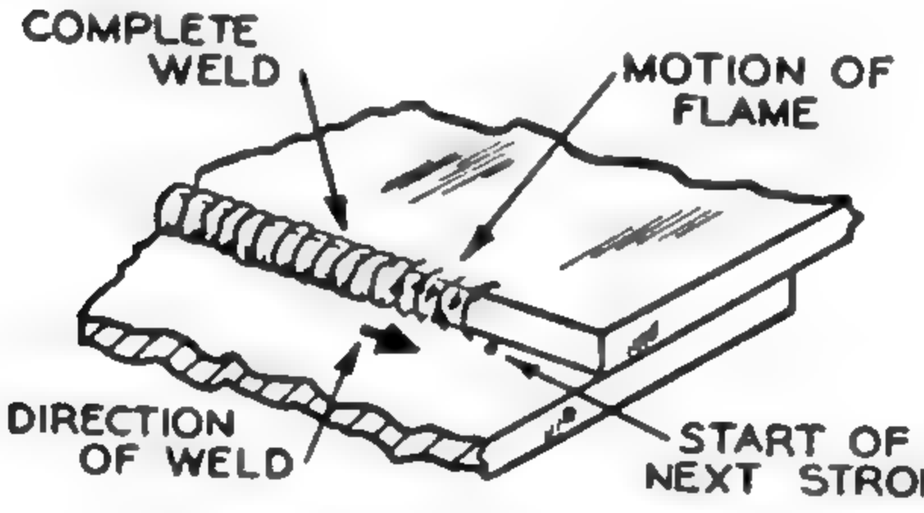


Fig. 7.—Technique of Welding Lap Joint in Flat Position

In welding in the horizontal position, a soft bushy flame is most desirable; in the vertical and overhead positions a more pointed flame is generally used. This will vary to some extent with each welder.

Positions of Welding

Welds in a Flat Position.—The butt joint is the most commonly used type for flat welding, and has been described previously. For thin sheet, $^1/_{32}$ to $^1/_{64}$ in. (2 to 4 lb.), flanges 1 to $1^1/_2$ times the sheet thickness may be bent up, cleaned and butted together. Lap joints are sometimes preferred, due to simplicity of fitting. Welding consists of moving the torch in a semicircular path toward the lap and then straight away. Filler metal is generally used, although none is used on the first pass. Flat welds are illustrated in Figs. 1, 2, 3 and 7.

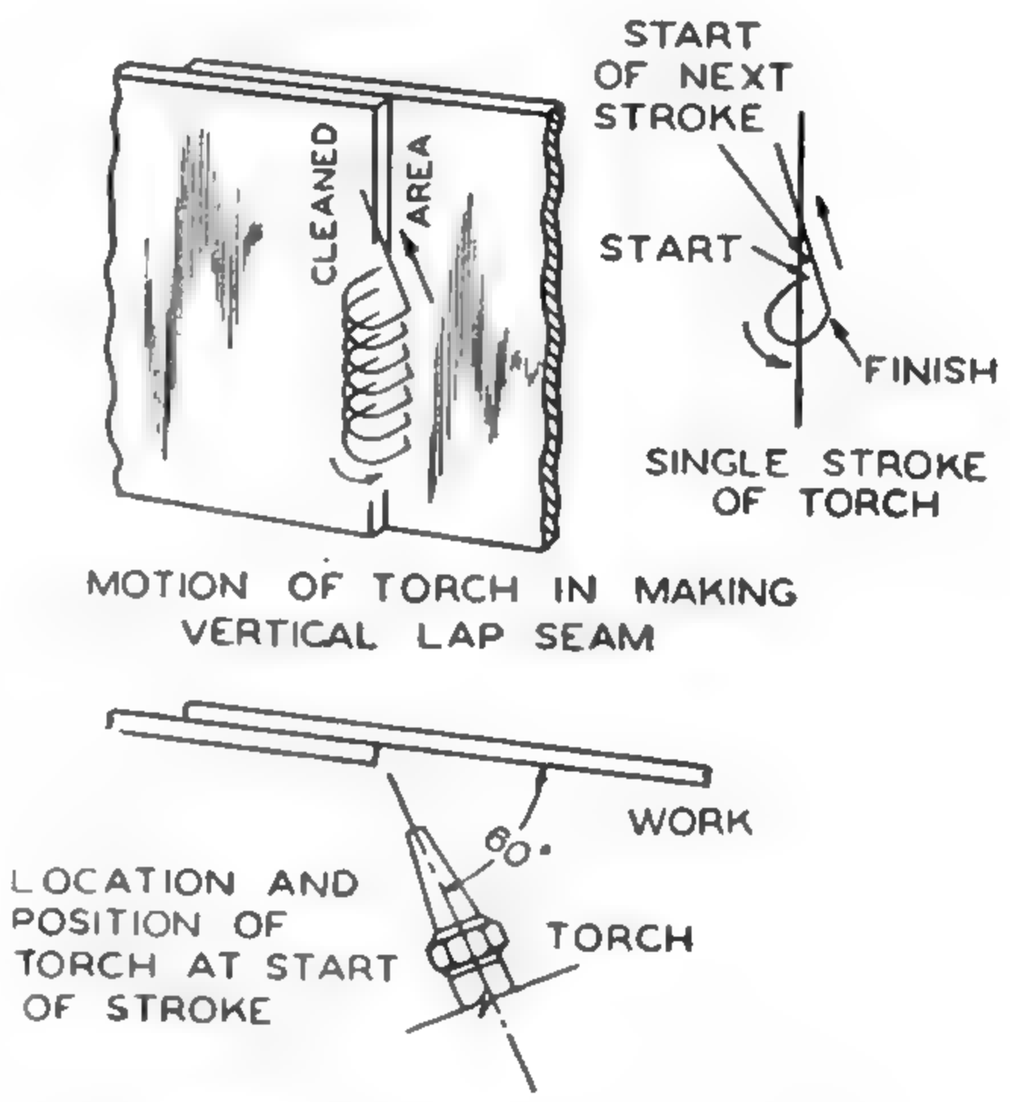


Fig. 8.—Technique of Welding Lap Joint in Vertical Position

Welds in a Vertical Position.—Lap joints are used almost exclusively for welding in the vertical position. Welding is begun at the bottom of the joint and the flame is applied to the lead at the junction of the front and rear sheets. When the edge of the front sheet becomes molten, the flame is carried with a circular downward motion back into the sheet and completely liquefying the overlap. Then the flame is carried almost horizontally over the underlapping sheet fusing the front and rear sheets together. Welding rod is not generally used. (See Fig. 8.)

In rare instances, butt joints are used but this is more of a molding operation performed with molds held in place and

lead melted into and fused with the joint by directing the flame into the mold.

Welds in an Overhead Position.—The overhead position is the most difficult of all for welding lead and is to be avoided if at all possible. However, if it is necessary to weld in this position, the lap joint is most suitable and as sharp a flame as possible must be used. Of necessity, the beads should be small and the operation completed as quickly as possible. No welding rod is used. The pressure of the flame and capillary attraction are usually sufficient to hold the molten lead in place.

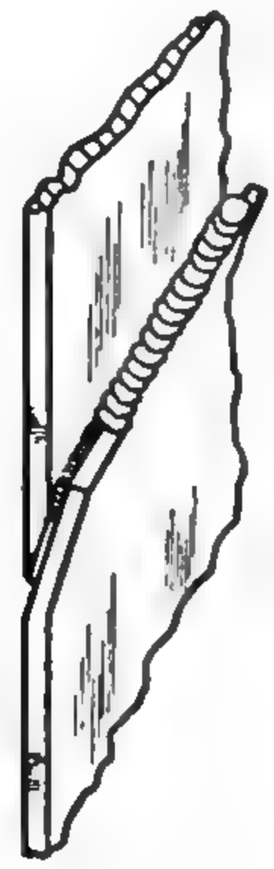


Fig. 9.—Overhand Technique for Welding in the Horizontal Position

Horizontal Joint on a Vertical Surface.—There are two methods of making joints in the horizontal position; the overhand, which is the easier and therefore the preferred, and the underhand. Both are of the lap type. In the so-called overhand method, the lower sheet to be joined is the overlapping sheet and the edge of the lap is left slightly open. The flame is inserted into this opening and welding done in what amounts to a flat position. (See Fig. 9.) The lap is not used as filler metal but becomes part of the flare in which the welding is performed. Filler metal is supplied by a welding rod. The underhand method is necessary if the upper sheet laps over onto the lower sheet. The lap is dressed tightly against the lower sheet and welding is performed by using the downside lap edge as filler metal. The flame is pointed at the lower sheet and cut into the overlap when the bead is formed. No welding rod is used. The underhand joint (see Fig. 10) is almost as difficult to weld as joints in the overhead position and should be avoided wherever possible.

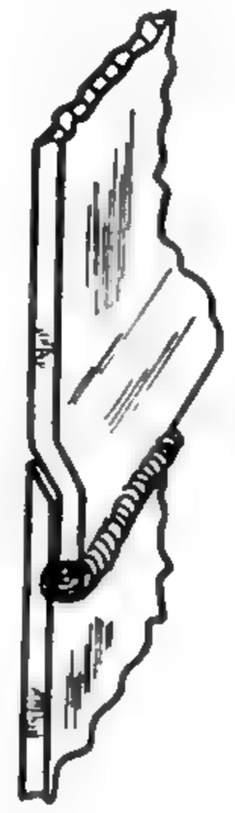


Fig. 10.—Underhand Technique for Welding in the Horizontal Position

Pipe Joints

For best results in welding pipe joints the work should be planned so that as few joints as possible have to be made in place. Where the pipe can be rotated horizontally, welding can be performed in what amounts to a flat position.

Where rolling is not possible and the pipe is in a horizontal position a butt joint is used. To avoid overhead welding the procedure usually followed is to cut a vee section in the upper part of one end of the abutting pipe. This allows access to the lower part of the joint which is then welded from the inside of the pipe.

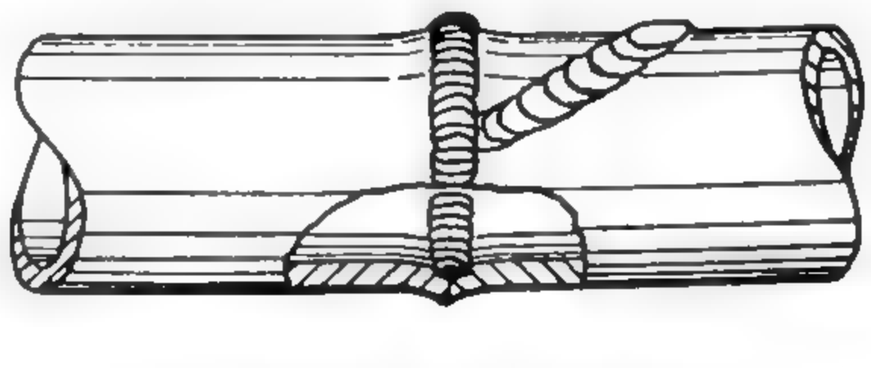


Fig. 11.—Technique for Welding Pipe in the Horizontal Fixed Position

The vee cut is then replaced and welded from the outside as is the upper part of the joint. (See Fig. 11.) An alternative method is to cut tee-slots in the upper part of both ends of the pipe, folding back the lead and following the same procedure as above.

For pipe joints in the vertical fixed position the cup joint should be used. The lower section of pipe is flared out and the upper beveled to fit into the flared end. The flame is directed into the flare and using the welding rod, the two sections of pipes are welded together. Multiple passes (loading passes) are usually necessary. The procedure of welding is similar to that used for a groove-welded butt joint. (See Fig. 6.)

Thickness of the Weld

From one to five layers of lead may be applied in welding, depending upon the thickness of the lead joined. In general, a weld reinforcement of about $^1/_8$ in. is used for butt joints. In flat lap joints, the rule is to build to the thickness of the top sheet and then apply one more pass. For vertical and overhead lap joints, multiple passes are seldom practical. For cup joints welded in the vertical fixed position, loading is necessary to bring the weld even with the lip of the cup.

Welding Lead to Other Metals

Welding lead to other metals is usually confined to a covering of lead applied to steel or copper. Lead-covered steel and copper are standard equipment and are commercially referred to as *homogeneously lined lead* equipment. The other metals are prepared for welding by thoroughly cleaning them by sand blasting or pickling. A considerable amount of this equipment is made by fluxing the steel or copper and applying the lead manually with torch and welding rod. Lead coatings of $^3/_{16}$ to $^3/_8$ in. are quite common. However, it is not usually possible to build up to these thicknesses in one pass and subsequent passes are necessary. No flux is necessary on these latter passes.

Important uses for these materials are in vacuum vessels, jacketed vessels and heat exchanger coils containing high pressures. This equipment gives relatively good heat transfer and withstands repeated rapid heating and cooling cycles without buckling.

Welding Speed

The speed of welding butt joints in the flat position is not much different from the speed of gas welding steel. Speeds of 30 ft. per hr. are common with 6-lb. sheet lead. Granjon's formula for determining welding speed is:

$$V = \frac{1.92 \text{ to } 3.85}{T}$$

where T = lead thickness, in.

V = welding speed, ft./hr.

Consumption of Welding Rod

On butt joints, a rough rule of thumb for rod consumption for a single pass is 1 ft. of rod to 1 ft. of joint where $^1/_4$-in. rod and 8-lb. lead are employed. There is slightly over 4 ft. per pound of $^1/_4$-in. rod.

Safety Precautions

Because of the toxic nature of lead, lead welding should be conducted in well-ventilated locations to prevent inhalation of excessive amounts of lead fumes or dust. Men working in confined areas, as the bottom of a deep open tank, should be provided with a positive air supply directed into the tank by a fan or blower to a position below the breathing level. In enclosed areas such as in a pressure vessel or closed tank, each man should be required to wear an air-supplied respirator or mask. (See Chapter 46 for further information on Safety in Welding.)

COMMON APPLICATIONS

Lead products which are welded include tank linings and conveyors and other equipment used to store, mix, convey or otherwise come in contact with chemical solutions. In lead storage batteries connector straps are welded to grids and connector lugs are welded to strap posts by a semi-automatic process.

Figure 12 is an example of lead welding a seam in 10-lb. sheet lead with a finger-tip torch in the collect launder of a 100-ft. diam. lead-lined settling tank, part of a set-up for purifying sulfur dioxide gas. Figure 13 shows workmen smoothing lead sheet and welding a seam in a lead floor pan being installed in a plating plant.

Welding of plumbing and roofing products is confined to waste and vent lines for chemical and laboratory tables. (See bibliography at end of chapter for sources of further information on the welding of lead.)

Supports for Sheet Lead Lined Tanks

Where high temperatures are used within the lead-lined tank or rapid cycles

Fig. 12.—Lead Lining a 100-Ft. Diam. Settling Tank

of heating and cooling are encountered or the tank is a large one, it is customary to reinforce the sheet lead lining with flat or half oval steel bars. This is done, after a complete lead lining is installed, by placing the steel bars over the lead lining and bolting them through to the outer surface of the tank. The exposed steel bars are then covered with strips of sheet lead that are welded to the lead lining. Where exceptionally severe conditions are encountered, brick linings within the lead linings are used.

B. ZINC

GENERAL PROPERTIES

Zinc and zinc alloys are similar in some respects to the group of metals which includes lead, tin and cadmium. Commercial grades of zinc conform to the requirements of ASTM *Standard Specifications for Slab Zinc (Spelter)* (Serial Designation: B6-46) and *Standard Specifications for Zinc-Base Alloy Die Cast-*

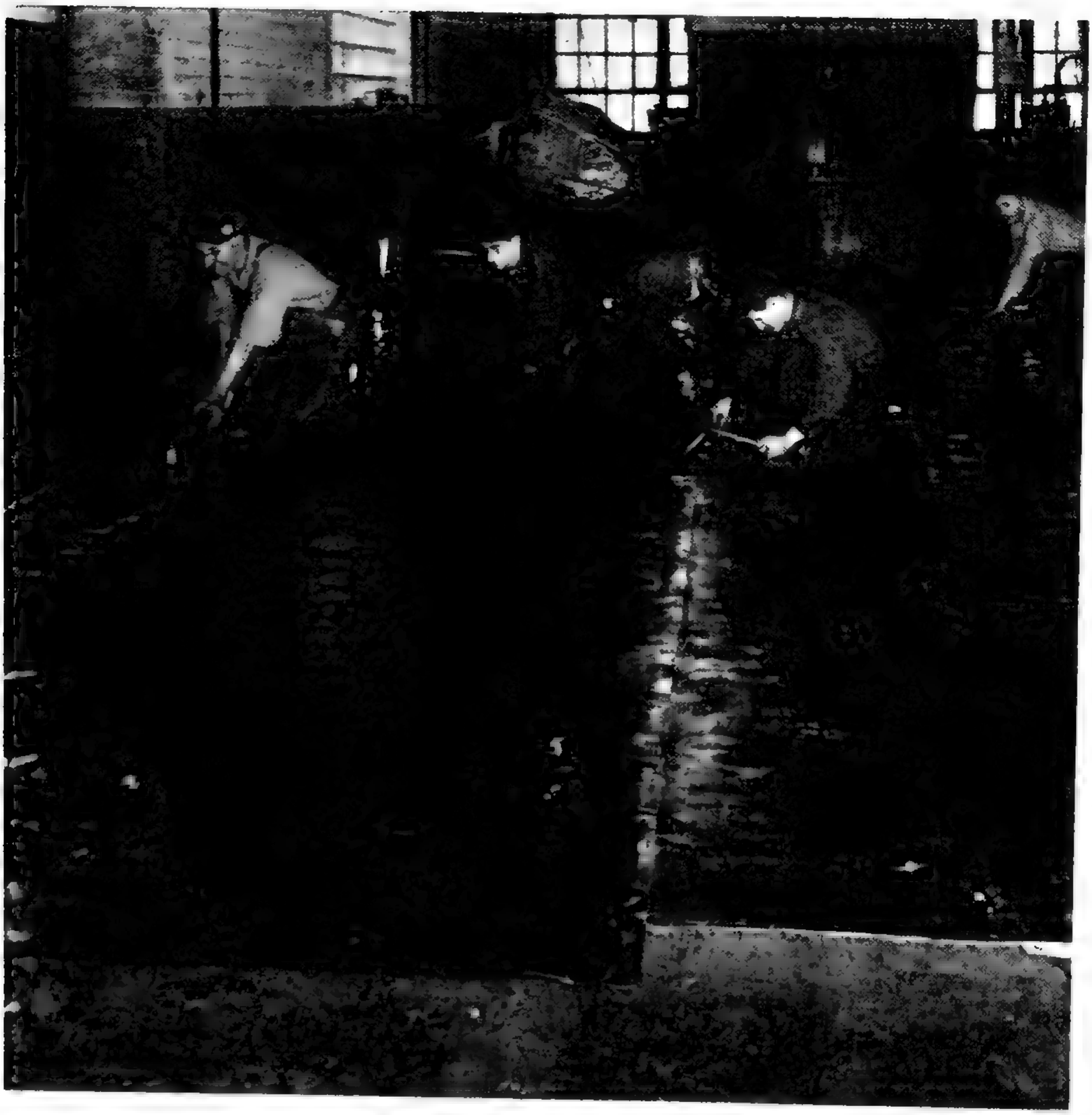


Fig. 13.—Lap Weld in Lead Floor of Plating Plant

ings (Serial Designation: B86-46), given in Tables 2 and 3.

Cast zinc and zinc alloys cannot be worked at room temperature, but may be rolled at about 300 to 500°F. or extruded at between 550 and 650°F. Wrought zinc sheet, however, is very ductile and can be fabricated at about 70°F., or slightly higher. However, zinc and zinc alloys become brittle somewhere below room temperature. Recrystallization decreases the ductility of zinc, particularly if large grains are formed. The mechanical properties of zinc sheet are highly directional, but zinc can be cross rolled in a continuous operation using properly proportional reductions to avoid directionality. The density of zinc is

Table 2—Chemical Composition of Slab Zinc

Grade	Lead, max., per cent	Iron, max., per cent	Cadmium, max., per cent	Aluminum	Sum of Lead, Iron, and Cadmium, max., per cent
(1a) Special High Grade	0.006	0.005	0.004	none	0.010
(1) High Grade	0.07	0.02	0.07	none	0.10
(2) Intermediate	0.20	0.03	0.50	none	0.50
(3) Brass Special	0.60	0.03	0.50	none	1.0
(4) Selected	0.80	0.04	0.75	none	1.25
(5) Prime Western	1.60	0.08	. .	. .	. .

NOTE.—Analysis shall not regularly be made for tin but when used for die castings, if found by the purchaser, tin shall not exceed 0.003 per cent. Greater amounts may constitute cause for rejection.

Table 3—Chemical Composition of Zinc-Base Alloy Die Castings

	Alloy No. XXI	Alloy No. XXIII	Alloy No. XXV
Copper, per cent	2.5 to 3.5	0.10, max.	0.75 to 1.25
Aluminum, per cent	3.5 to 4.5	3.5 to 4.3	3.5 to 4.3
Magnesium, per cent	0.02 to 0.10	0.03 to 0.08	0.03 to 0.08
Iron, max., per cent	0.100	0.100	0.100
Lead, max., per cent	0.007	0.007	0.007
Cadmium, max., per cent	0.005	0.005	0.005
Tin, max., per cent	0.005	0.005	0.005
Zinc, per cent	remainder	remainder	remainder

7.14, less than iron. Its melting point is 787°F. while it boils at 1665°F. Its electrical conductivity is about one-third that of copper.

HOW TO WELD

Processes Used

Gas welding is most commonly used for welding zinc and zinc alloys although spot and seam welding have been used to fabricate wrought zinc parts. (See Chapter 16.)

Working Precautions

Since zinc surfaces oxidize instantaneously, making shaving impractical, a flux has to be used in welding. This flux not only prevents oxidation, but evaporation and boiling in the weld puddle are limited as well. The flux is usually a half-and-half paste of zinc chloride and ammonium chloride (sal ammoniac). Zinc alloys containing 4% aluminum require special attention, since fluxing is difficult.

The evaporation of zinc from the weld puddle, which occurs at 1112 to 1292°F. results in the formation of a fume of zinc oxide above the weld. Chapter 46 contains information on the hazard of zinc fumes and suggestions for ventilation.

The principal requirement for successful oxy-acetylene welding is that flux be applied on both edges of the sheet and on the welding rod, so that metal of the same composition as the base metal will be deposited.

Preparation for Welding

The torch tip should be small in order to keep the amount of welding heat at a minimum. A tip suitable for steel $^1/_{32}$-in. thick is used for zinc $^1/_8$-in. thick. The flame should be neutral or slightly reducing. The joint is prepared in about the same way as for steel. Thin sheets, $^1/_{32}$-in. thick are flanged and welded without the addition of filler metal. Square-edged butt joints are welded in material up to $^1/_8$-in. thick. Thicker zinc is beveled to form a 70- to 90-deg. groove angle. Tacking at intervals of about 4 to 6 in. is helpful. Lap joints are used sometimes to save time in fitting the edges. The welding technique is similar to that for aluminum in that holes are formed if the torch is held vertically. Therefore, the torch is held at an angle of 15 to 45 deg. to the sheets. On the other hand, in welding zinc the flame is directed on the welding rod which is lifted out of the flame for an instant after each drop has been deposited. It seems to be immaterial whether the flame is pointed toward or away from the deposit. The rod may be used to stir the puddle and coalesce the molten metal, while the torch is given an oscillating motion to avoid dwelling too long on one spot and melting a hole. Sheets $^1/_8$-in. thick have been butt welded at the rate of 25 ft. per hour.

Butt or lap joints in the vertical position are started at the bottom. Either the torch is applied periodically to form a succession of beads or the torch is held nearly parallel to the sheets to melt the seam continuously.

Peening the weld at 200 to 300°F. refines the grain size and may improve the mechanical properties. Peening at room temperatures or above 300°F. may crack the weld.

Welding Zinc-Base Die Castings

Broken zinc-base die castings as thin as $^1/_{32}$ in. have been oxy-acetylene welded successfully by a number of experts, provided the castings have not been oxidized Welding is difficult because of the alumi

num that these alloys contain, and is confined to repair work. The edges to be welded may be filed or may be scraped to a V with a steel spatula after being heated to the sweating point. The welding rod may be pure zinc or, preferably, a die-casting alloy of the same type as that to be welded. Flux is recommended by some authorities (50% $ZnCl_2$, 50% NH_4Cl), but most operators use none because alumina* cannot be fluxed at welding temperatures, 602–788°F. A reducing flame is generally preferred but no soot should be deposited. The flame should be directed on the welding rod to prevent overheating the casting. It appears to be better to direct the flame nearly parallel to the surface rather than nearly vertical. Plaster of Paris is used sometimes to support the casting during welding, while a graphite mold may be used to prevent liquid weld metal flowing away while the weld is being stirred.

* Aluminum oxide.

COMMON APPLICATIONS

Zinc is used mainly for galvanizing and its weldability is frequently a factor when welding galvanized materials. Brasses contain a high percentage of zinc and also can be welded. (See Chapter 34.)

Zinc alloys containing aluminum are sometimes welded or brazed because soldering is difficult unless the alloy is electroplated with an adequate coating of copper or nickel. This applies to die castings and also to stamping die alloys.

BIBLIOGRAPHY

1. *Lead Welding, A Review of the Literature to January 1940*, W. Spraragen and G. E. Claussen, The Welding Journal Res. Suppl., February 1941.

2. *Lead Welding*, R. L. Ziegfeld and D. M. Borcina, Steel, August 5, 1946.

3. *Lead Welding Practices*, L. S. Bowser, The Welding Journal, September 1947.

4. *Lead Welding*, R. L. Ziegfeld and D. M. Borcina, Journal of the United Association of Journeymen and Apprentices of the Plumbing and Pipe Fitting Industry, December 1947.

5. *Welding Zinc, Tin, Bismuth, etc., A Review of the Literature to June 1939*, W. Spraragen and G. E. Claussen, The Welding Journal Res. Suppl., June 1940.

CHAPTER 37A

CLAD STEELS*

GENERAL PROPERTIES

Definition

A CLAD STEEL PLATE is a composite plate made up of commercial grade steel plate, to one or both sides of which there is continuously joined a veneer or cladding of a corrosion and/or heat-resisting metal, the thickness of which is an appreciable proportion of the total plate thickness.

Method of Manufacture

Clad steels may be manufactured by any of the following methods:

Roll Welding (Heat and Pressure Methods).—A heavy slab of steel of the desired mechanical and chemical properties is thoroughly cleaned on one of its flat surfaces. A plate of the specified cladding material, with one surface specially prepared, is placed on the steel slab (see Fig. 1). All cladding plates containing chromium are first given an anodic pickle in dilute hydrochloric acid followed by an electrolytic plating of a layer of nickel or iron on one side. This prevents the formation of a chromium-oxide film on the surface to be bonded to the steel base plate.

A second similarly prepared slab of steel and cladding material is placed on top of the first one with an infusible parting compound separating the clad surfaces. The assembly is held together and sealed from contamination by a continuous weld around the perimeter. The composite *sandwich* or slab is heated in a soaking pit to a temperature of 2100 to 2350°F., depending upon the type of cladding, and rolled in a mill. The rolling pressure reduces the thickness of the composite material and bonds the cladding to the steel, maintaining the

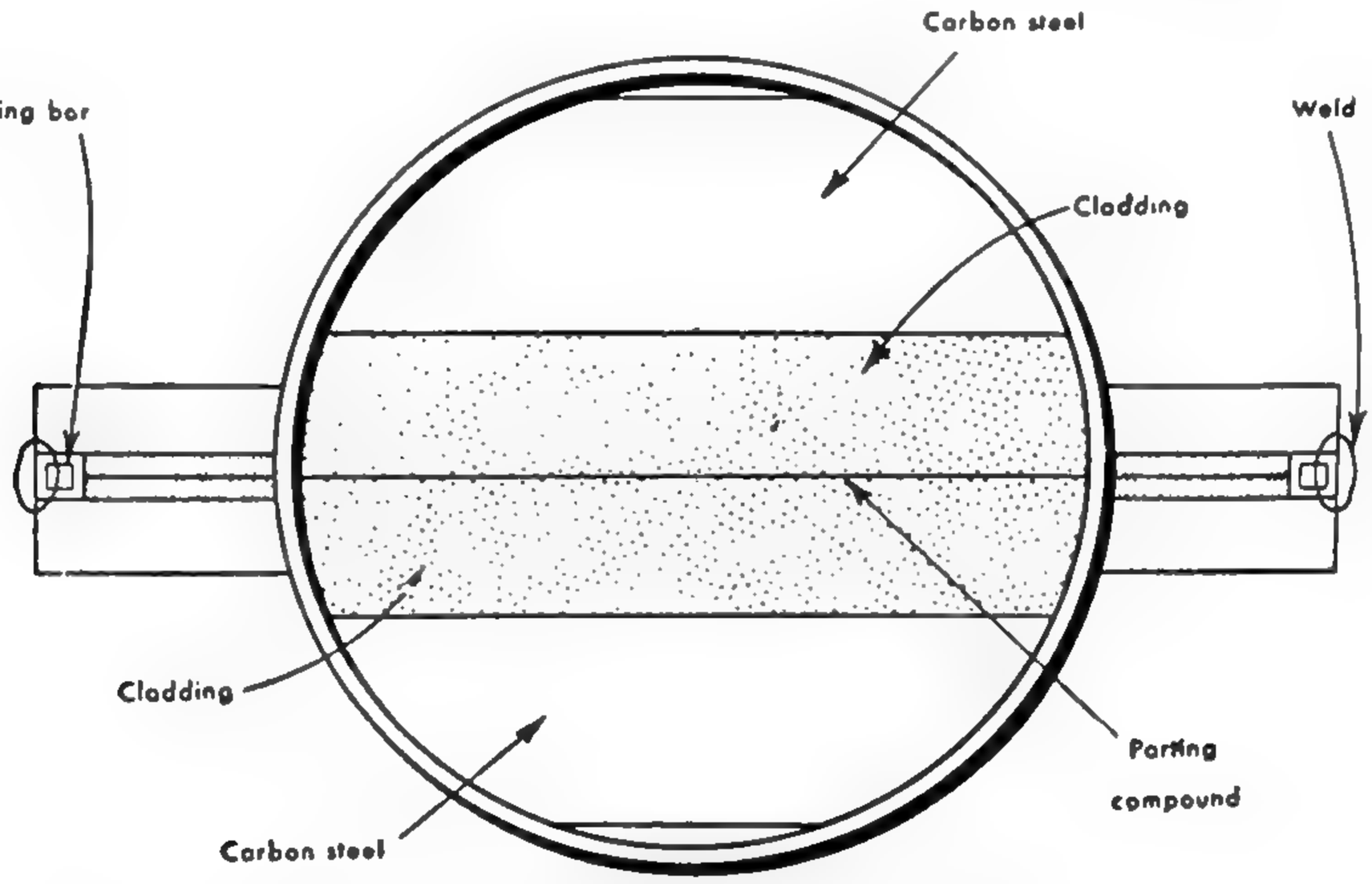


Fig. 1.—Clad Steel Plate Made by Roll Welding

* Prepared by a committee consisting of W. G. Theisinger, Lukens Steel Co., *Chairman;* H. S. Blumberg, The M. W. Kellogg Co.; O. B. J. Fraser, The International Nickel Co.; L. W. Williams, Lukens Steel Co.

same relative proportions from the assembled slab to the rolled plate. After rolling, the four edges of the slab are sheared or oxygen cut and then separated into two clad plates, each of which consists of a steel backing with a layer of clad metal permanently bonded to one surface. Plates clad with stainless steel are heat treated after rolling to improve corrosion resistance.

Casting Method.—Using this method, cladding may be applied to a mild steel plate by casting mild steel around an assembly of two plates of the cladding separated by insulating material and welded around the perimeter as shown in Fig. 2. The composite assembly is then rolled as in the heat and pressure method and separated into two plates of clad steel by shearing of all four edges.

Materials Available

The backing plate of a clad steel may be carbon steel or low-alloy steel of flange quality or better conforming to the ASTM Specifications or similar specifications of the ASME Boiler Code. The most commonly used backing materials are as follows:

A201—Specifications for Carbon-Silicon Steel Plates of Ordinary Tensile Ranges for Fusion-Welded Boilers and Other Pressure Vessels, Grades A and B.

A203—Specifications for Nickel-Steel Plates for Boiler and Other Pressure Vessels, Grades A, B and C.

A204—Specifications for Molybdenum-Steel Plates for Boilers and Other Pressure Vessels, Grades A, B and C.

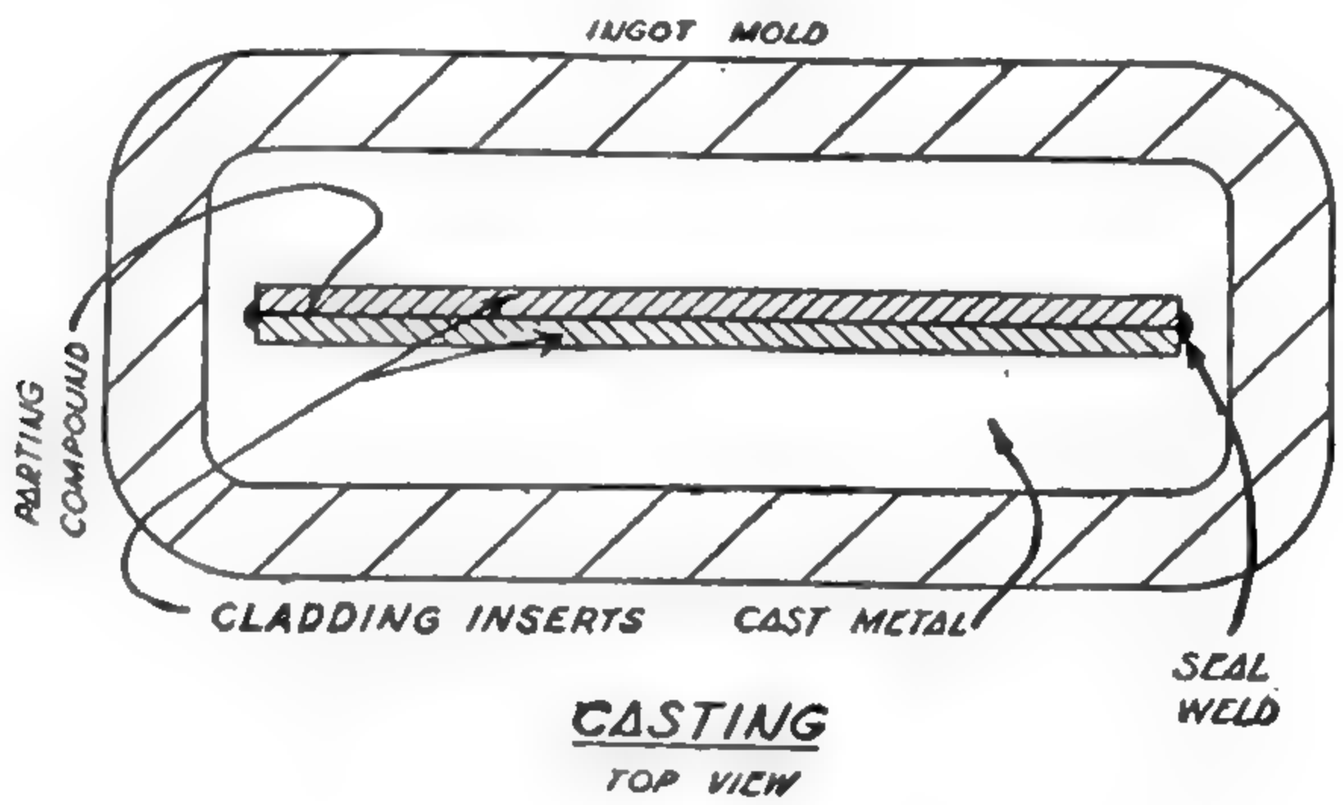


Fig. 2.—Clad Steel Plate Made by Casting Method

Intermelting Method.—In this method a refractory wall forms the bottom and three sides and a steel slab forms the fourth side of an open-top mold as shown in Fig. 3. In this jacketed space the alloying ingredients are metered and intermelted with the surface of the steel ingot by a special electric furnace to produce an integrally-bonded cladding of uniform composition. The clad plate is heated and rolled to the required thickness in a mill in the usual manner.

Arc and Gas Welding.—Overlapping beads of weld metal of the required composition may be deposited by shielded metal-arc welding, atomic hydrogen welding or oxy-acetylene welding onto one face of a mild steel slab as shown in Fig. 4. The clad slab is then ground, heated and rolled in the usual manner.

A212—Specifications for High Tensile Strength Carbon-Silicon Steel Plates for Boilers and Other Pressure Vessels, Grades A and B.

A225—Specifications for Manganese-Vanadium Steel Plates for Boilers and Other Pressure Vessels, Grades A and B.

A285—Specifications for Low and Intermediate Tensile Strength Carbon Steel Plates of Flange and Firebox Qualities (Plates 2 in. and Under in Thickness), Firebox or Flange Grades A, B and C.

The materials normally used for cladding are shown in Table 1. Other claddings such as copper or silver can also be obtained. Forms available include sheared flat plates and sheets in essen-

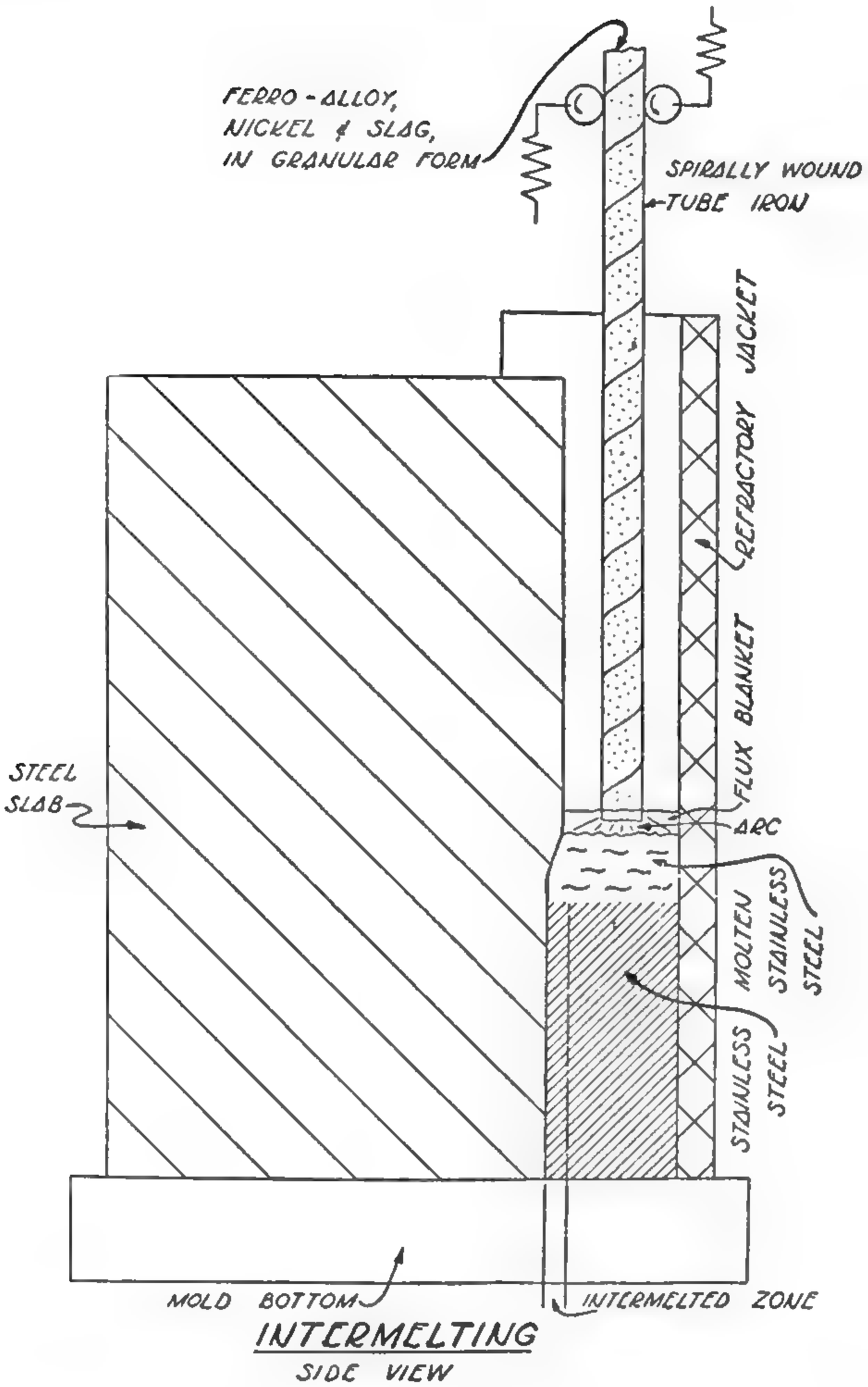


Fig. 3.—Clad Steel Plate Made by Intermelting Method

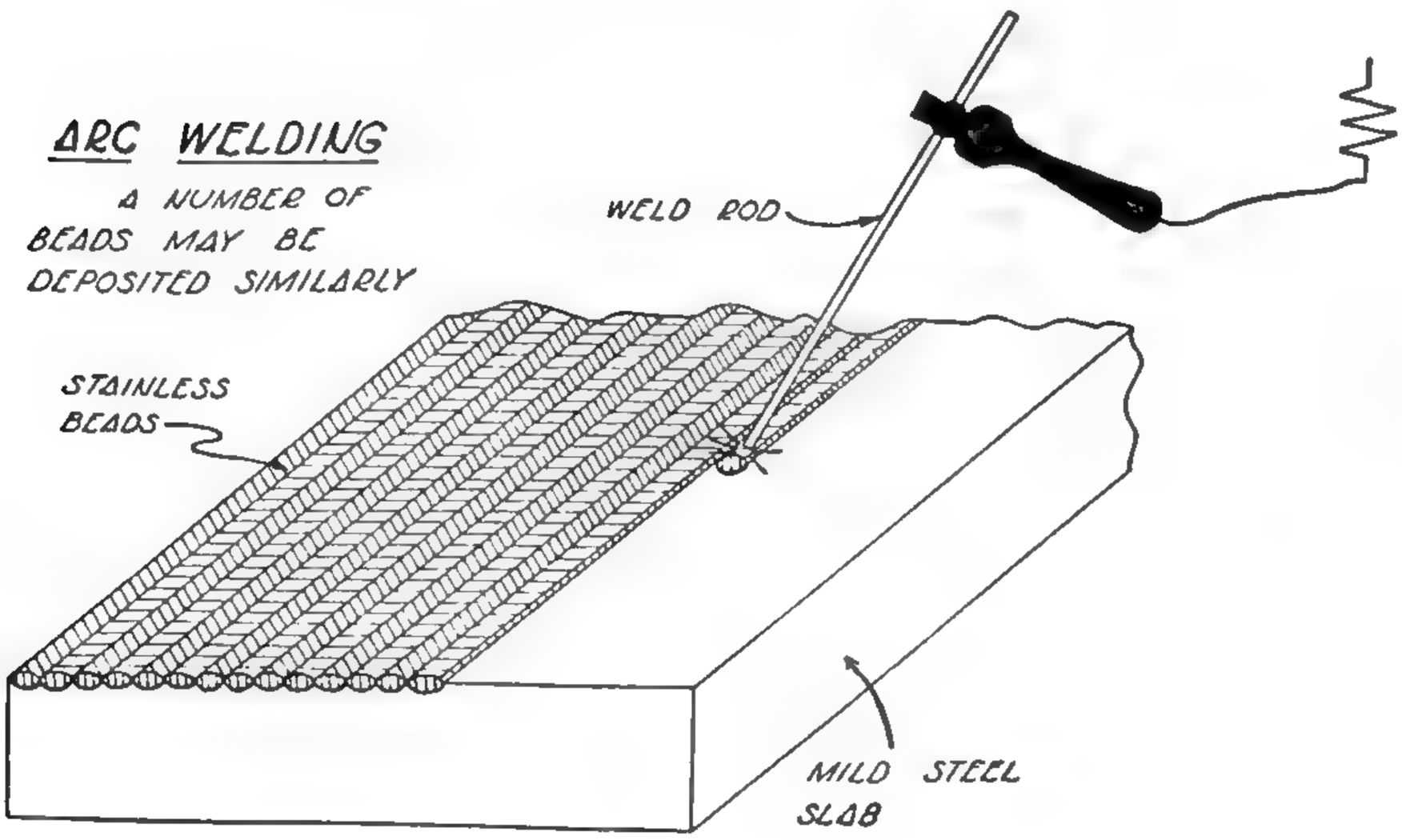


Fig. 4.—Clad Steel Plate Made by Manual Arc Welding

tially the same sizes and thicknesses as commercially rolled; and pressure-vessel heads, flanged, flanged and dished, elliptical and conical, some of which are shown in Fig. 5. In addition, flued opening and flared ring sections for manholes and handholes, flanges and practically any other shape can be made. Pressed tank manhole flanges for storage tanks are available and may be used to advantage with flared and dished covers for low-pressure vessels. (Refer to Chapter 31 for more detailed information on stainless steel and Chapter 35 for more detailed information on nickel and its alloys.)

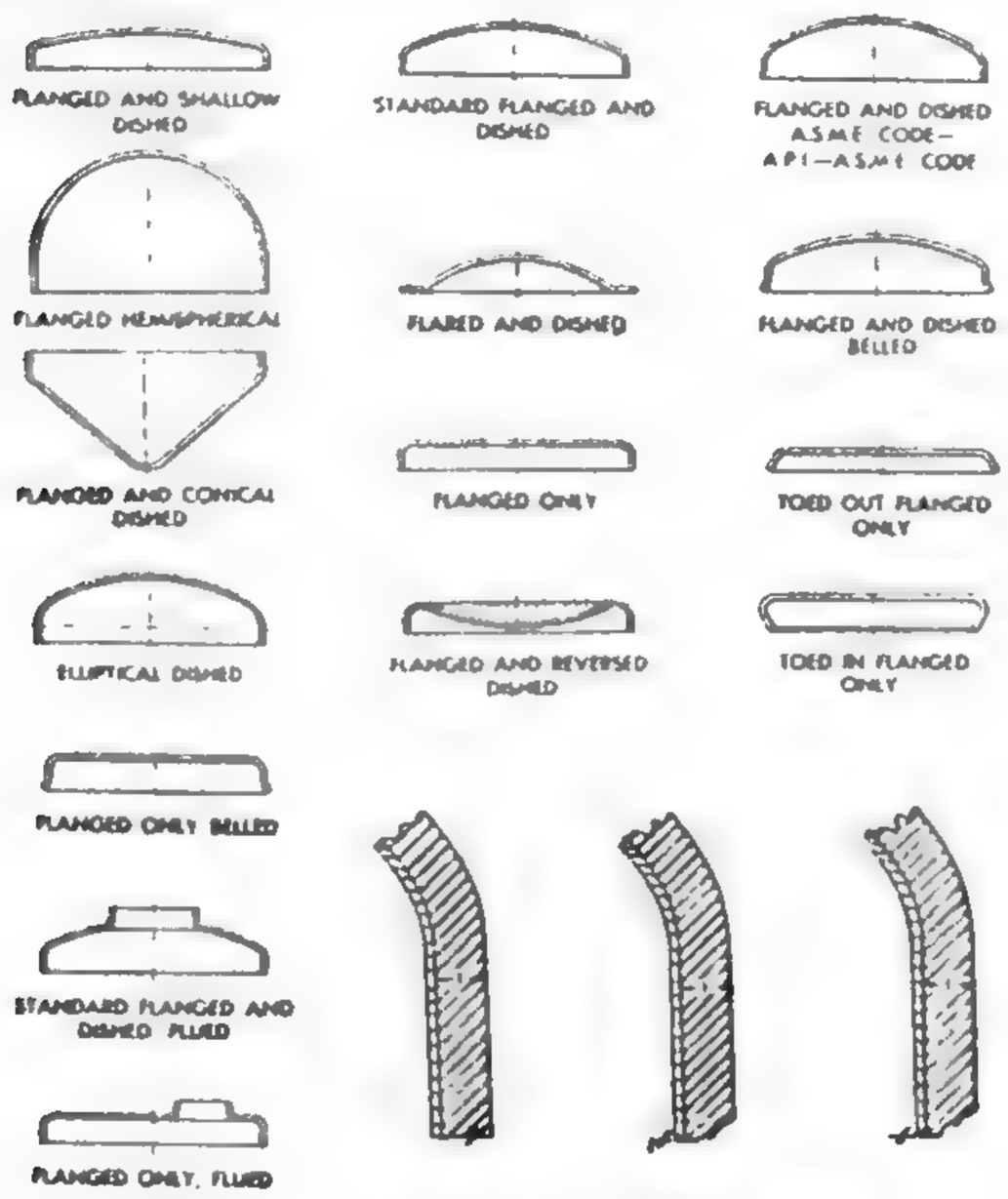


Fig. 5.—Typical Clad Steel Heads

Mechanical Properties.—The mechanical properties of clad steel plate, as determined by tensile test are equal to or better than the properties of the backing steel itself. Because of the large selection of backing materials available, advantage can be taken of the high-tensile strength of carbon-silicon or low-alloy steels, or the elevated or subzero temperature properties of molybdenum or nickel steels, respectively. Backing materials of special analyses may also be used.

Cladding Thicknesses.—The cladding thickness is normally specified as a percentage of the total thickness of the composite plate. The most common thicknesses are 10 and 20%, but the thickness may vary from 5 to 50%. Cladding thicknesses may also be specified in fractions or decimals of an inch, such as $^{7}/_{64}$ in. or 0.050 in. regardless of the total thickness of the composite plate. The thickness of cladding used is determined by the requirements of the application, but for fabricating reasons is generally held to 0.030 in. minimum.

Thermal Conductivity.—Vessels made of clad steels (except nickel-clad steel which corresponds to solid nickel's high heat conductivity) have a noticeably higher rate of heat transfer than solid corrosion-resistant materials or lined vessels. Due to the intimate contact between the cladding and the backing material and the adherence of the bond, there is no significant thermal resistance. The efficiency in heat transfer of clad steel is almost equal to that of solid carbon steel.

Cleaning and Treating

In order to avoid contamination of clad surfaces with shop dirt a protective paper coating may be pasted on the clad surface, or it may be sprayed with a plastic coating. Before welding, it is necessary to remove a strip of the coating, from 1 to 3 in. wide depending on the thickness, along the edge to be welded. To prevent burning, plastic coatings should also be removed from the clad surface when attachments are to be welded on the unclad side.

Plates should be handled in the shop with the clad side up to prevent gouging and deep scratching. Bending rolls, dies and tools should be wiped or brushed clean of loose scale and metal particles that might become imbedded in the cladding.

Cleaning.—Clad steel plates may be descaled by sandblasting or by the sodium hydride process. In this latter process the plate is immersed in a bath of molten caustic soda (sodium hydroxide) at 700°F., containing 1.5 to 2.0% sodium hydride. The sodium hydride reduces the scale to lower metal oxides or to metal. The plate is cooled by water quenching during which the steam liberated loosens the oxide from the surface. The clad surface of the plate is brightened by immersion in an acid bath. Plates clad with stainless steel are also passivated with nitric acid. After high-pressure spraying with water, the plates are given a hot-water bath from which they dry quickly. Heads and other parts as well as plates may be descaled by this method

Table 1— Composition Ranges of Alloy Cladding Materials

Popular Name	ASTM Type	AISI Type Number	Carbon, Max., %	Manganese, Max., %	Phosphorus, Max., %	Sulfur, Max., %	Silicon, Max., %	Chromium, %	Nickel Max., %
			A—Chromium Steel Cladding						
12 Chrome	A-263 Grade O	405[a]	0.08	1.00	0.040	0.040	1.00	11.50–13.50	0.60
12 Chrome	Grade A	410 (modified)	0.12[b, c]	0.60	0.030	0.030	0.75	12.00–14.00	0.60
15 Chrome	Grade B	.....	0.12[b]	1.00	0.030	0.030	0.75	14.00–16.00	0.60
16 Chrome	Grade D	430 (modified)	0.12[b]	1.00	0.030	0.030	0.75	16.00–18.00	0.60
			B—Chromium-Nickel Steel Cladding						
17–7	A-264 Grade 1	301	0.08–0.20	2.00	0.035	0.030	1.00	16.00–18.00	6.00–8.00
18–8	Grade 2	302	0.08–0.20	2.00	0.035	0.030	1.00	17.00–19.00	8.00–10.00
18–8	Grade 3	304 (modified)	0.08[b]	2.50	0.035	0.030	0.85	18.00 min.	8.00 min.
19–9	Grade 4	308	0.08	2.00	0.035	0.030	1.00	19.00–21.00	10.00–12.00
18–8Ti	Grade 5[d]	321 (modified)	0.08[b]	2.50	0.035	0.030	0.85	17.00 min.	9.00 min.
18–8Cb	Grade 6[e]	347 (modified)	0.08[b]	2.50	0.035	0.030	0.85	17.00 min.	9.50 min.
25–12	Grade 8	309	0.20	2.00	0.035	0.030	3.50	22.00–24.00	12.00–15.00
25–20	Grade 10	310	0.25	2.00	0.035	0.030	2.00	24.00–26.00	19.00–22.00
18–8Mo	Grade 11[f]	316 (modified)	0.08[b, g, j]	2.50	0.035	0.030	0.85	17.00 min.	10.00 min.

Popular Name	ASTM Type	Carbon, Max., %	Manganese, Max., %	Sulfur, Max., %	Silicon, Max., %	Chromium, %	Nickel,[j] %	Copper, Max., %	Iron, Max., %	Al, Max., %
		C—Nickel and Nickel-Base Alloy Cladding								
"L" Nickel[k]	...	0.02	0.35	0.01	0.35	..	99.00 min.	0.20	0.40	..
Nickel	A-265 Nickel	0.20	0.35	0.02	0.50	..	99.00 min.	0.25	0.50	...
Monel	Nickel-copper alloy	0.30	2.00	0.02	0.50	.	63.00–70.00	Remainder	2.50	0.50
Inconel	Nickel-chromium-iron alloy	0.15	1.00	0.02	0.50	12.00–15.00	75.00 min.	0.50	9.00	...
Super Nickel[l]	Copper-nickel alloy	..	1.00	..	.	. .....	29.0–33.0	Remainder	0.60	..

[a] Aluminum 0.10 to 0.30%.
[b] The carbon analysis shall be reported to the nearest 0.01%.
[c] Available with 0.06% max. C.
[d] Grade 5 shall have a titanium content of not less than five times the carbon content nor more than 0.60%.
[e] Grade 6 shall have a columbium content of not less than ten times the carbon content nor more than 1.0%.
[f] Grade 11 shall have a minimum molybdenum content of 2.0%.
[g] Available with 0.03% C max.
[h] Available with columbium. (Not referred to in ASME Specifications.)
[j] Includes a small amount of cobalt.
[k] Not referred to in ASTM Specifications but in analysis range of specifications.
[l] Not referred to in ASTM specification

which removes all the scale without loss of metal.

Heat Treating.—Controlled treatments and procedure are necessary to produce the desired corrosion-resistant and mechanical properties in clad steels. Conventional-type equipment is used; time and temperature control are most important and cannot be overemphasized. Muffle-type furnaces are desirable. The material should not be exposed to a direct flame if gas or oil is used as fuel.

Table 2—Maximum Hot Working and Annealing Temperatures

Cladding[a]	Maximum Hot Working Temp.[b], °F.	Annealing Temperature Range, °F.	Rate of Cooling, Hr.
12% Cr	2100[c]	1400–1500	[d] [c] [e]
12% Cr	2000[c]	1450–1550	[d]
15% Cr	2000[c]	1450–1550	[d]
16% Cr	2000[c]	1450–1550	[d]
17–7Cr-Ni	2100	2000–2150	[e]
18–8Cr-Ni	2100	1850–2050	[e]
18–8Cr-Ni	2100	1800–2000	[e]
19–9Cr-Ni	2100	1800–2000	[e]
19–9Cr-Ni-Ti	2100	1800–2000	[e] to
19–9Cr-Ni-Cb	2100	1800–2000	[e] to
25–12Cr-Ni	2100	2050–2150	[e]
25–20Cr-Ni	2100	2050–2150	[e]
18–12Cr-Ni-Mo	2100	1900–2150	[e]
Nickel[g]	2300	1500–1600	[e]
Monel	2150	1600–1700	[f]
Inconel	2300	1750–1850	[e]

[a] See Table I for chemical analyses.
[b] Do not heat above maximum temperature of hot working range
[c] Work to below 1500°F. for maximum grain refinement.
[d] Furnace cool at 50° per hour to 1100°F., then air cool.
[e] Air quench.
[f] Can be annealed at 1500–1650°F. for 2 hr. per in. thickness.
[g] Special low-carbon "L" nickel should be used if extensive hot work or annealing is required.

Steels having a stainless cladding require a neutral or oxidizing atmosphere. Reducing atmospheres should be avoided as they may produce carburizing conditions that result in the loss of corrosion resistance. Furthermore, the oxidizing atmospheres produce a scale that is more easily removed than that formed by a reducing atmosphere. In contrast, steels having a nickel, Monel or Inconel cladding should be heated in a reducing atmosphere; otherwise, surface or edge cracking may develop during hot working caused by prolonged heating in the upper portion of the hot-working temperature range.

Fuels high in sulfur, such as coke, coal, unwashed producer gas, crude oil and others having a sulfur content in excess of 0.5%, may destroy ductility of the cladding through embrittlement.

Clad steels should have marking paint and protective oil removed from the clad side before heating. Embrittlement or corrosive action may start from grain boundary failure caused by zinc or sulfur, or from the carbonization of organic compounds.

Clad steel plates should be supported on clean steel rails or on clean fire brick to keep the clad surface from contact with the slag or cinders in the furnace bottom. Wherever possible, the plates should be heated *with the clad side up.*

In general, the difference in the coefficients of expansion of the backing metals and the cladding will give little or no trouble upon applications of heat. In most cases, prolonged soaking during heating is to be avoided because of the possibility of embrittlement, oxidation, excessive grain growth and, in the case of the unstabilized austenitic stainless clad steels, carbide precipitation in the temperature range of 800 to 1600°F. Thickness and composition of cladding and backing plate will establish the definite type of treatment required.

Preheating may be desirable to prevent thermal shock when rigid sections, different thicknesses of clad steel, or heavy gage material with high percentages of cladding are being heat treated.

The holding time at the required temperature, as shown in Table 2, should be only long enough to insure that all the material is thoroughly heated. Any additional time may produce undesirable grain growth.

Rate of Cooling.—Steels clad with

straight chromium steel, except Type 405, should be furnace cooled at a rate not exceeding 50°F. per hour to 1000°F., then air cooled to produce maximum ductility. Type 405 stainless steel may be air cooled from the annealing temperature since it has low hardenability.

Hot Working.—Clad steel should not be heated above the temperatures shown in Table 2. The hot metal should be handled carefully to prevent damage to the clad surface. The clad material may be worked exactly as unclad steel plate. Dies should be dressed to remove burrs which might gouge the cladding. With straight chromium steel cladding, the work should be worked down to below 1500°F. to secure maximum grain refinement. Hot working should be followed by suitable heat treatment to insure proper condition of the material for service.

Material Preparation

Shearing and Punching.—Shearing and punching should be done *with the clad side up* to throw the burr on the steel side. If sheared clad plates are to be welded, consideration should be given to shear droop, which is the break in flatness that occurs on the sheared edge due to the shearing pressure. This effect can be disregarded where the plate edge is subjected to subsequent machining operations, or if the plate is of light gage.

Bending and Rolling.—When severe bending or other forming is performed, the material should be in the annealed condition. Radii should be as large as possible and compensation for spring-back should be made when bending. When low-alloy steel backing is used for heavy-gage clad plate, bending and rolling should be performed hot. All working surfaces of both the plate and the machine must have loose scale and steel particles or chips removed so they will not be imbedded in the clad surface and act as focal points for corrosion. The straight-chromium-clad materials are not as ductile as the other clad materials, and allowance should be made for this factor in both design and fabrication. When certain corrosive applications require that the cladding be free from any stresses arising from severe cold working, such stresses should be removed by annealing.

Machining.—The backing plate may be machined with speeds and feeds used for mild steel. With chromium-nickel claddings, the tool should not be allowed to ride the clad surface, as the material will work harden and gall. With all types of cladding, the speeds should be a little lower than those used for steel, but feeds should be firm.

Oxygen Cutting.—When oxygen cutting plain-carbon steels, the cut is effected by successive oxidation of the metal and removal of the oxide. With clad steels, however, the cladding must be removed by actual melting of the alloy. Steels clad with nickel, chromium steel or chromium-nickel steel are readily cut, but some difficulty may be experienced in cutting Monel and Inconel claddings. It is general practice to preheat steels clad with these two materials to a dull red in advance of the cut.

The material should be cut with the backing steel on top, and all scale should be removed along the line of cut. The nozzle or tip should be one or two sizes larger than that ordinarily used for the same gage of unclad carbon steel, and it is recommended that the nozzle be of the type having six preheating orifices rather than the usual four. An ample volume of cutting oxygen should be provided to assist in the washing action. The torch should be inclined 5 to 20 deg. toward the direction of cut (see Fig. 6) to aid in production of slag which washes the cladding material away from the line of cut. The correct angle of tip can be determined by experimentation only, on account of differences in fuels and equipment.

Too small an angle of tip causes flame impingement on the cladding without penetration, resulting in loss of the cut. When the angle of the tip is large, it is sometimes found that the plates will not be cut through completely at the finish of the cut. To overcome this difficulty the finished section of the cut should be preheated to a dull red which will eliminate the loss of cut.

Preheat should be used at the start of all cuts. In thicknesses up to and including $^1/_4$ in., with 10% cladding, it is only necessary to preheat locally at the start using the cutting tip. In heavier gages, and also in the lighter gages of 20% cladding, it is recommended that preheating be used at the start of a cut, using a regular torch. The material should be preheated to a dull red. Care should be taken, when starting a cut, that

the preheating flame does not interfere with the fluxing action of the backing steel on the cladding. With cladding of Monel or Inconel, it is recommended that the plate be preheated, manually or mechanically, just ahead of the cutting tip for the entire length of cut.

Embrittlement of straight-chromium cladding and carbide precipitation in chromium-nickel stainless (except in the stabilized grades) cladding, found along the line of cut, should be given consideration. The extent of the marginal heat-affected area into the plate along the

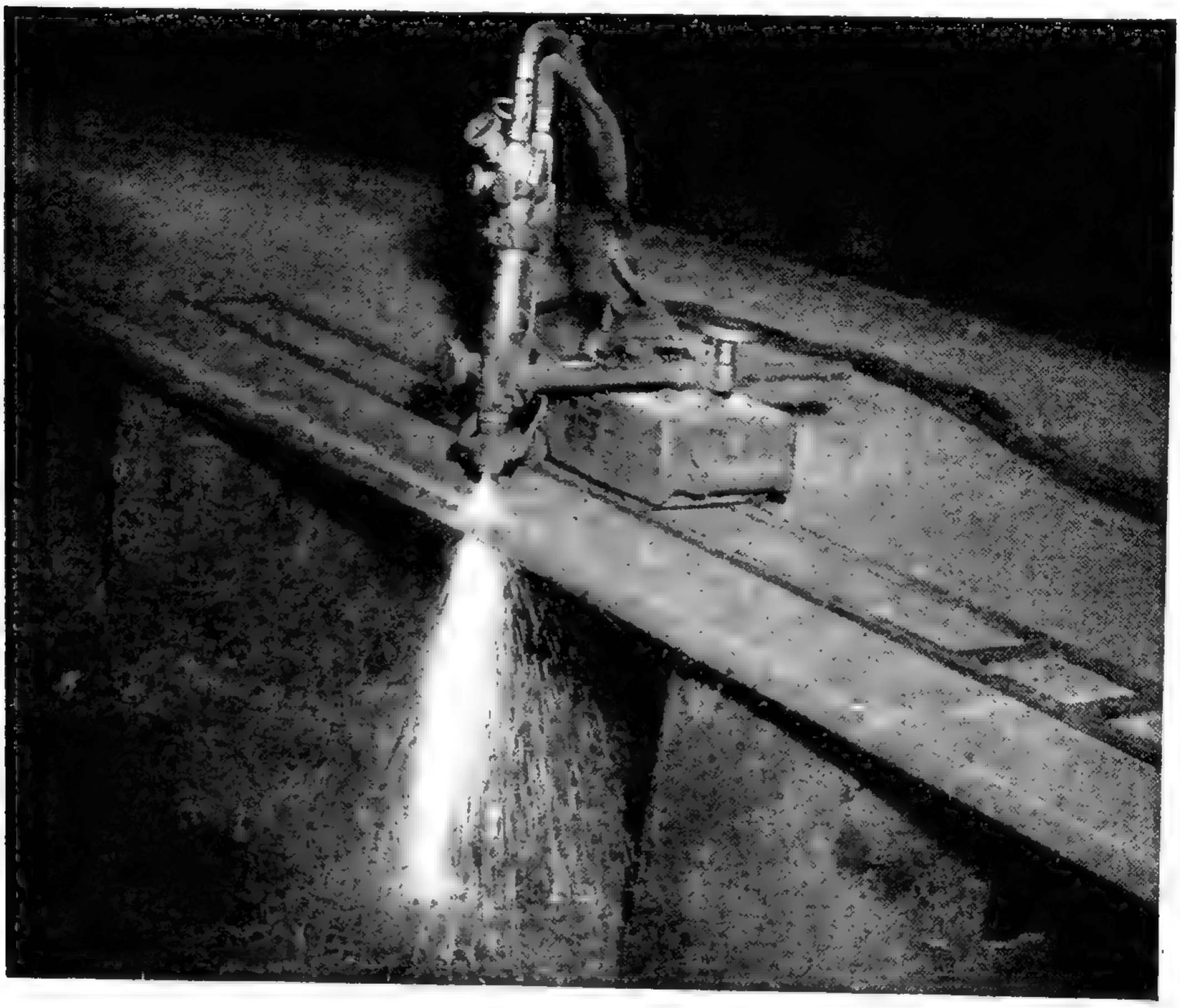


Fig. 6.—Oxygen Cutting Stainless-Clad Plate

Clean and smooth cuts can be obtained in all clad materials. The proper relationship between tip size, gas pressure, speed of cutting, plate thickness and percentage of cladding can be established by experimentation under operating conditions in the fabricating shop.

The necessary edge preparation on the steel backing can be obtained by oxygen gouging.

Preheating before cutting may be advisable with straight-chromium cladding if the plates are thick, or if the cladding percentage is high, to prevent cracking and lack of ductility.

line of cut will depend on the speed of cutting and the plate thickness. The affected material should be removed by grinding or machining, if the plate cannot be subsequently annealed, to improve the ductility or to remove precipitated chromium carbides. (See Chapter 24 for more detailed information on oxygen cutting.)

Flux-oxygen cutting, described in detail in Chapter 24, may be used to cut clad steels; oxy-arc cutting, described in detail in Chapter 25, may also be used. Clad materials are cut easily from either side by the above processes (see Fig. 7).

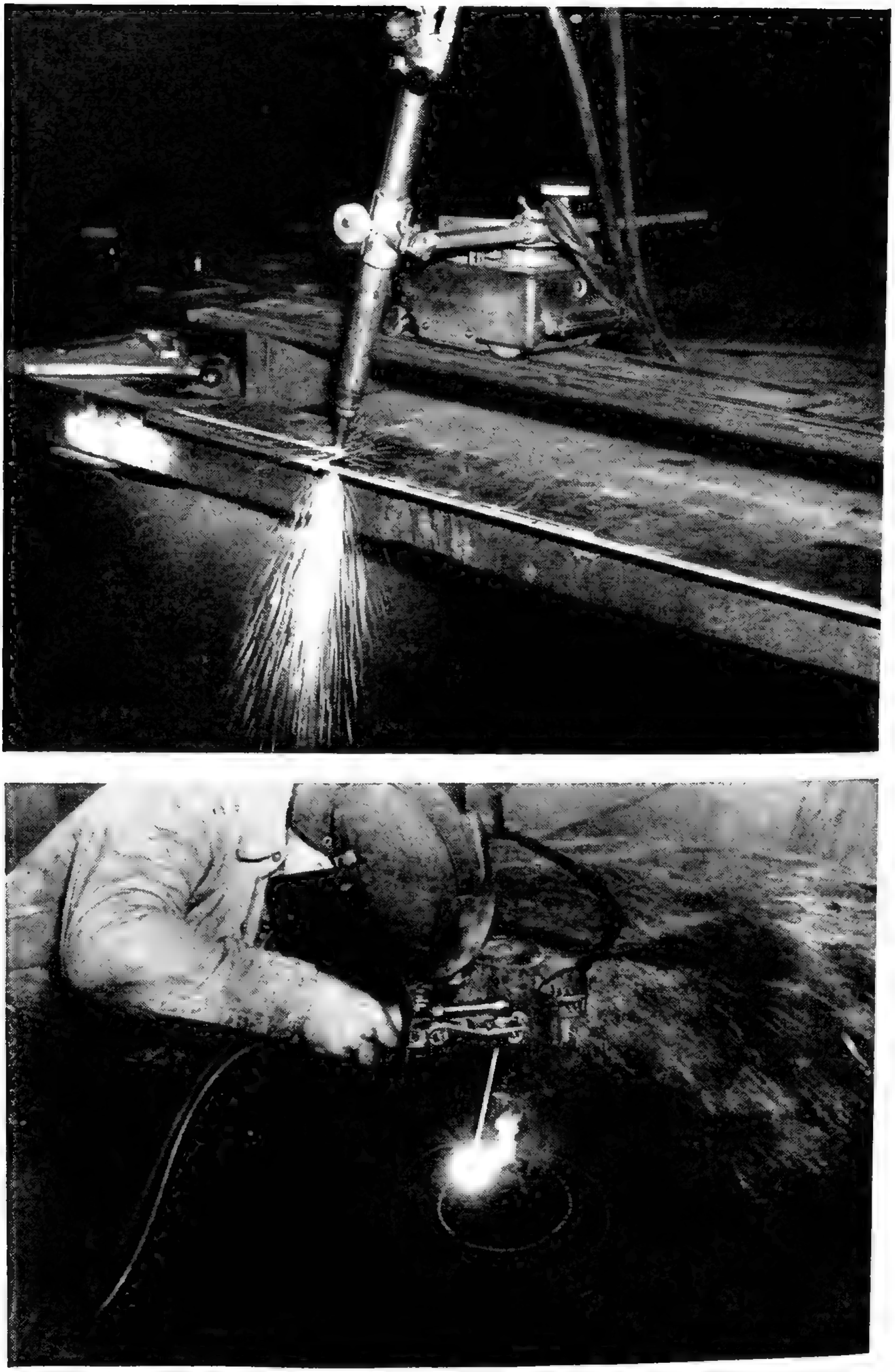


Fig. 7.—Cutting Stainless Clad Steel
(Top) By flux-oxygen process.
(Bottom) By oxy-arc process.

HOW TO WELD

General

Materials used as claddings are selected for their corrosion-resistant and heat-resistant properties. Therefore the retention of these properties must be considered at all times. Since the weld joining clad plates becomes a section of the corrosion-resistant surface, it must not only provide adequate strength but must maintain the integrity of the clad surface. Clad materials are readily welded when proper joint designs and welding procedures are used.

Processes Applicable

Shielded metal-arc welding is generally employed for joining clad steel thicker than 18 gage.

Atomic hydrogen welding is commonly used for joining silver clad and light gage clad metals of other compositions.

Inert-gas metal-arc welding, using either argon or helium, may be used for light gage clad metals.

Submerged arc welding is used on heavier gage metals for the steel side.

Brazing is sometimes used on very light gage material.

Gas welding is seldom used for clad steels and resistance welding has had no application to this group of materials.

For further information on any of these processes refer to the chapter covering that process.

Shielded Metal-Arc Welding

No preparation, other than proper shearing, is necessary for butt welds in the lighter gage clad sheets. Wherever possible, the joint should have a small root opening. For the thinner gages, about 18 to 16 gage, the electrodes should be carefully chosen and the welding done from the cladding side in one pass. From about 14 to 11 gage, the weld may be made in two passes, the first from the clad side and the second from the steel side. A $^{3}/_{32}$-in. diam. electrode is recommended. The weld from the steel side may also be made with covered steel electrodes of the same diameter (see Fig. 8).

In welding the intermediate gages, from about 10 gage to $^{3}/_{16}$-in. thick plate, beveling of the groove face on the steel side is usually recommended. However, if desired, sheets in this thickness range may be welded with square edges following the procedures outlined in the preceding paragraph, in which case the clad side should be welded first. Where it is more desirable or economical to make a composite weld in this thickness range, the steel side should be beveled and welded first with a covered steel electrode (see Fig. 8).

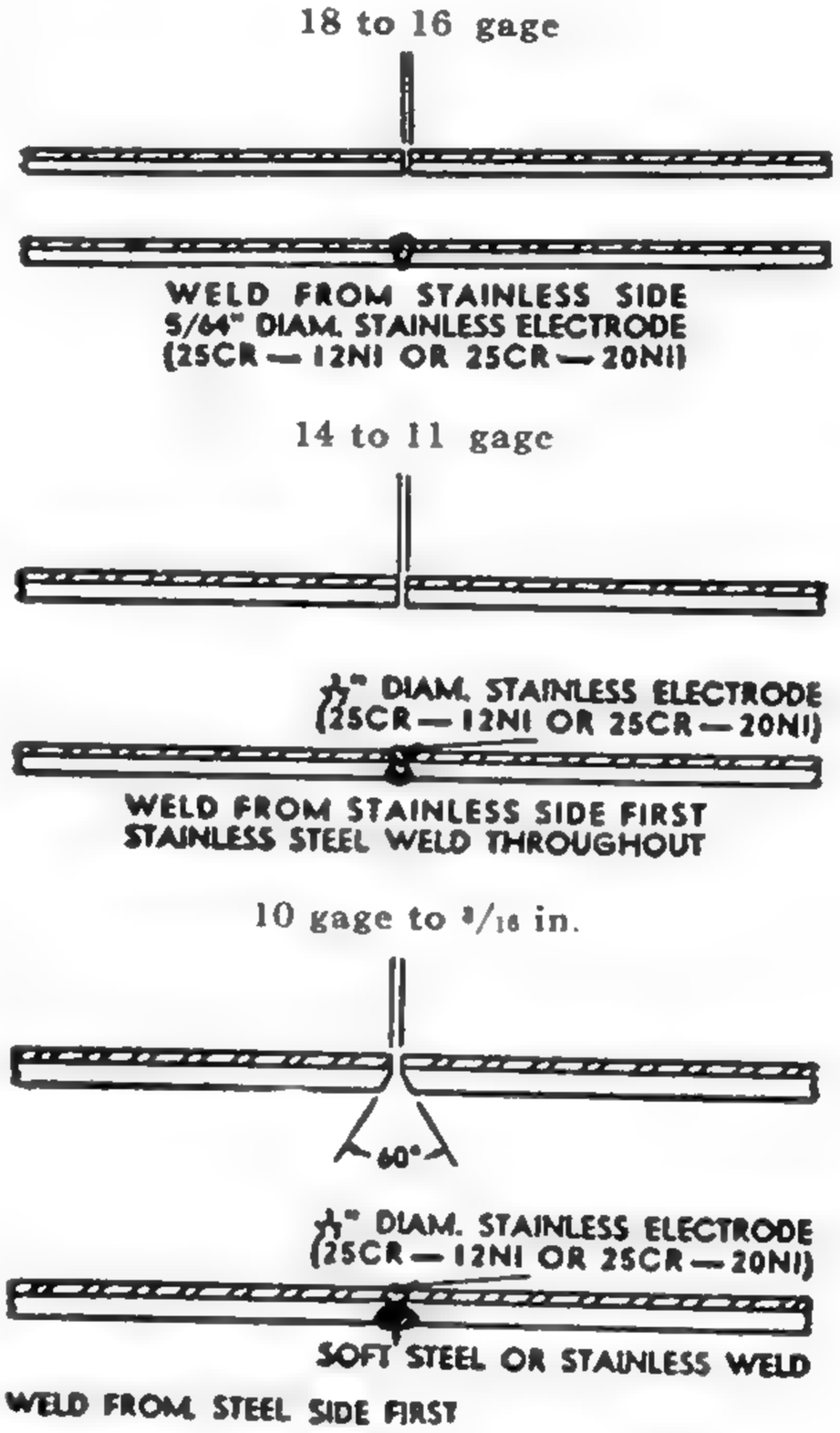


Fig. 8.—Methods of Arc Welding Light-Gage Clad Steels

After the steel weld deposit is laid down, the slag must be thoroughly removed from the clad side of the weld groove before attempting to weld the clad side. The second weld should be made in a single pass with a $^{3}/_{32}$-in. diam. electrode.

The preferred procedure in the welding of a butt joint in heavier material, up to $1^{1}/_{4}$ in. thick, is described below. This procedure should be used on all types of clad materials (see Fig 9).

Plate edges should be machined accurately maintaining a root face of $^{1}/_{16}$ in. plus $^{1}/_{32}$, minus 0 above the cladding. This root face should be of uniform thickness, as it acts as a barrier to prevent contamination of the mild steel weld

metal by the high alloy cladding material.

The members should then be assembled and the clad edges aligned. Tack welds should be made on the steel side with any good grade of carbon steel electrodes or the edges held together with suitable assembly devices. Good fit-up and alignment are the most important steps in the production of the joint.

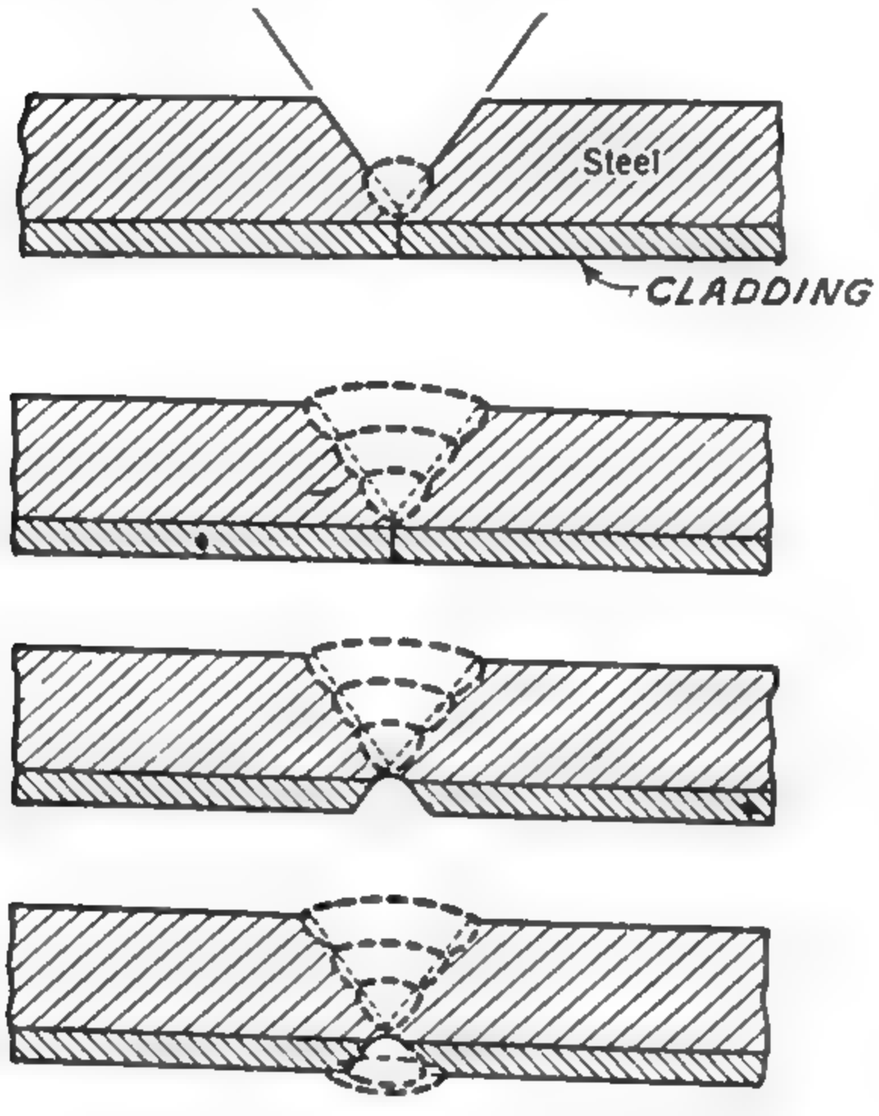


Fig. 9.—Sequence for Arc Welding Heavier Clad Steels

The weld on the steel side is completed, using an electrode that will develop the required characteristics of the backing material. The root bead should penetrate to the bottom of the steel, but should not penetrate into the cladding. If this bead penetrates into the high-alloy cladding material, an extremely hard and brittle material lacking in ductility will be formed.

Close control of the depth of penetration of the root bead on the steel side is one of the most important factors in producing a clad weld. This control is obtained by the use of a larger angle of bevel than used for steel welding and/or by use of smaller diameter electrodes. The care required to produce adequate, but not excessive, penetration of the root pass is more than justified when consideration is given to the reduced amount of back chipping or grinding required and the minimum consumption of high-alloy, higher-cost electrodes.

If the cladding is penetrated by the steel root bead due to poor fit-up, improper joint design or the use of too hot or too large an electrode, martensite will be formed in the root pass. Since martensite is lacking in ductility, such difficulties as cracking, inability to back chip or a combination of these highly undesirable characteristics may result. When the penetration of the steel root bead is inadequate, the area to be removed by chipping or grinding from the clad side will be excessive and large amounts of alloy weld metal will be required.

Welding electrodes for the steel side should be selected to possess the tensile strength of the backing steel. When special backing steels are used for high- (molybdenum steels) or low- (nickel steels) temperature properties, the electrode composition should be of the same analysis, or one that will produce the required properties.

When welding in the flat position, E6020 or E6030 electrodes should be used. The root bead should be welded with proper current and a rather high rate of travel to control penetration. In the vertical or overhead position, E6010 or E6011 electrodes should be used. Care should be taken to obtain proper penetration of the root bead.

Good fit-up is the most important factor in the successful welding of clad steels. In cylindrical vessels, where heads are to be attached, it is important that the plates be laid out to match the inside diameter of the heads. Spun heads thicken up on the straight flange section and the thickness is not predictable. For this reason, it is necessary to check the individual heads and match the shell plates to them.

If the fit-up is poor, E6013 electrodes should be used in all positions to reduce penetration and danger of pickup of the cladding material.

Suggested current ranges for the different electrodes used in welding the steel side are shown in the chart below.

		Current, Amp.				
AWS Type		E6010	E6011	E6012	E6020	E6030
Current and Polarity		D.C., Rev.	A.C.	D.C., Str. or A.C.	D.C., Str. or Rev.	A.C. or D.C.
Electrode Diam.	1/8	80–120		90–130	110–150	
	5/32	120–160		120–180	130–190	
	3/16	140–220		140–220	180–230	
	1/4	200–300		200–300	250–330	
	5/16	250–400		250–400	350–450	

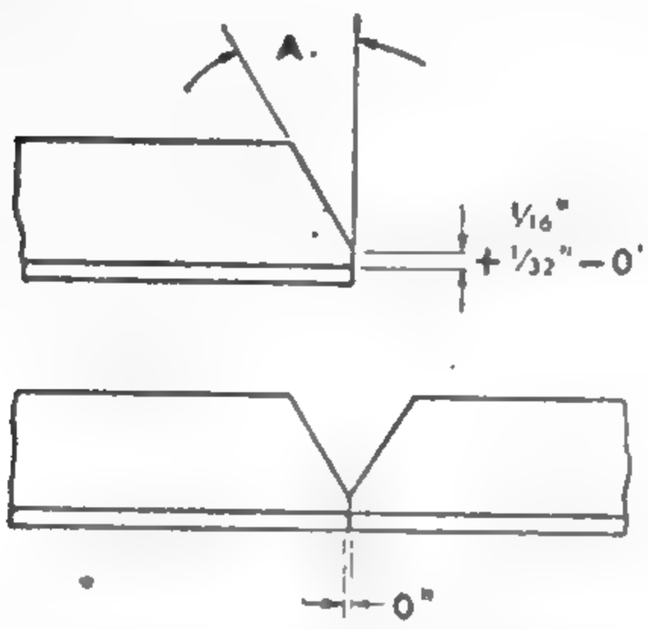
The high side of the range may be used for flat or horizontal welding, while the medium values should be used for vertical welding. (Refer to Tables 3, 4 and 5.)

Chipping or grinding, or both, can be used to prepare the clad side of the joint after the steel side has been welded. It is necessary to chip or grind down to clean sound weld metal prior to any alloy welding. This removes the unfused area that would act as a stress raiser and also removes the slag remaining from the backing steel weld that might gasify upon application of the alloy beads and produce porosity.

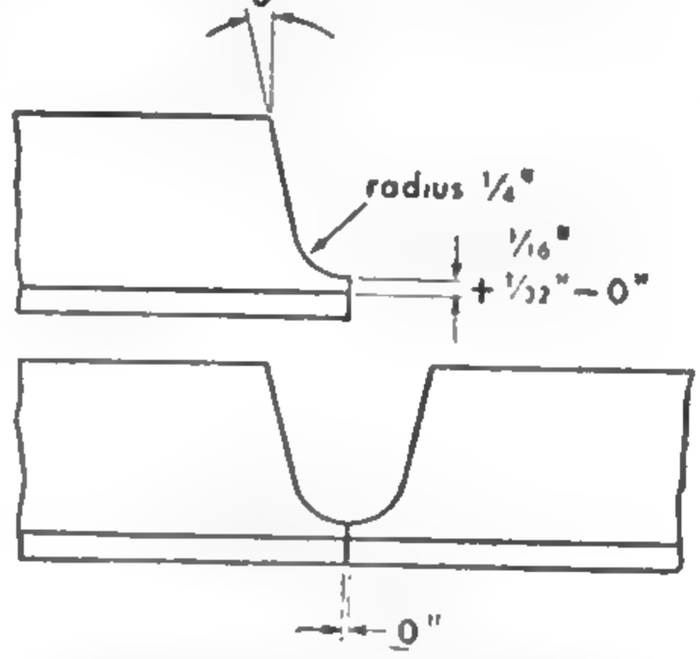
When grinding the clad side, it is customary to use a high-speed cut-off wheel. It is often advantageous to chip a light groove to provide a guide for the grinding wheel, as the high speed of the grinder has a tendency to throw the wheel. Normally, on clad plates up to $^1/_8$-in. thick, a $^1/_8$-in. thick, 6-in. diam. wheel is used for the initial cut. After the groove is ground to the required depth, a $^1/_4$-in. thick, 6-in. diam. wheel is often used in order to open up the top section of the groove and provide adequate space in which to manipulate the welding electrode. On heavy cladding, a $^1/_4$-in. thick wheel should be used for the first cut, followed by a $^3/_8$- or $^1/_2$-in. thick wheel to provide adequate width of groove. Extreme care should be taken when grinding to assure that sound metal has been exposed. The high-speed grinding operation tends to smear the metal and hide unfused sections.

The question has arisen regarding welding of the clad side first in order to prevent pickup of the steel backing material by the alloy welding metal. This procedure generally results in hard, brit-

Table 3—Procedures for Welding Steel Side in Flat Position



Single-Vee Groove Welds



Single-U Groove Welds

Material Thickness, In.	Angle, Deg. A	Angle, Deg. B	Single Vee Passes	Single Vee Elect. Diam., In.	Single U Passes	Single U Elect. Diam., In.
1/4	45	..	1	1/8	...	...
			2	5/32		
3/8	45	..	1	1/8	...	...
			2 & 3	5/32		
1/2	45	..	1	1/8	...	...
			2 & 3	5/32		
3/4	35	10	1 & 2	5/32	1	5/32
			Bal.	3/16 or 1/4	2–6	1/4
1	30	10	1 & 2	5/32	1	5/32
			Bal.	3/16 or 1/4	2 & 3	1/4
					Bal.	1/4 or 5/16
1 1/4	30	10	1 & 2	5/32	1	5/32
			3 & 4	3/16	2 & 3	1/4
			Bal.	1/4 or 5/16	Bal.	1/4 or 5/16
1 1/2	.	10	...	...	1	5/32
					2 & 3	1/4
					Bal.	1/4 or 5/16
2	..	10	...	...	1	5/32
					2 & 3	1/4
					Bal.	1/4 or 5/16

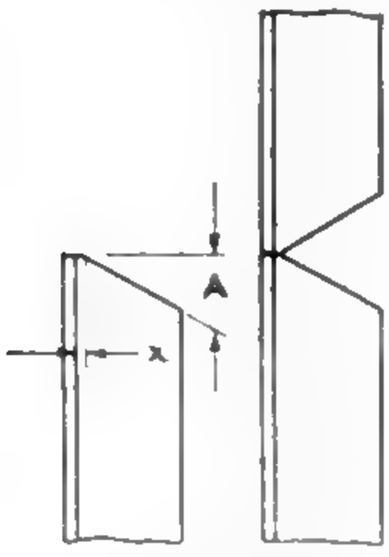
tle steel weld metal, as the alloy weld metal and cladding material are picked up by the steel weld metal. The amount of pickup will range from 10 to 40%. When mild steel is welded on high-alloy material the cooling rates will result in a hard brittle material. When an alloy is welded on steel, however, the deposited weld metal will be soft and ductile.

The depth of the chipped or ground groove is controlled by the extent of the unfused root face. When proper welding procedures are coupled with good workmanship the depth of the groove below the cladding should not be more than $^1/_{16}$-in. or one-half the cladding thickness in heavy-gage plates. Copper sulfate-hydrochloric acid solution may be used in the chipped or ground groove to determine whether the unfused area has been removed.

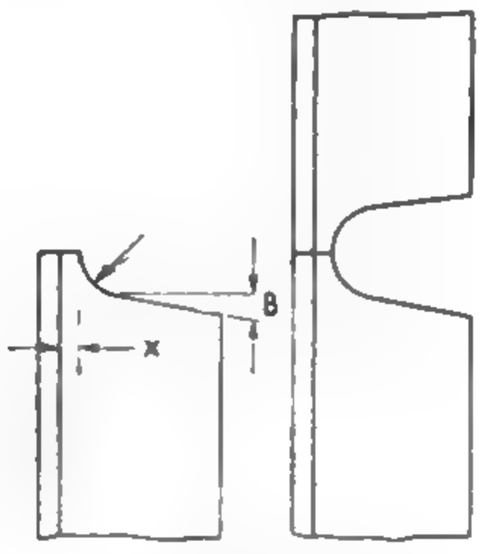
If the depth of the groove is excessive, a steel bead may be applied from the clad side, taking care to prevent pick-up or penetration of the cladding.

The width of the chipped or ground groove should be held to approximately the dimensions shown below. If the depth of the groove is excessive, due to lack of penetration in the steel side, the width should be increased proportionately to allow electrode manipulation.

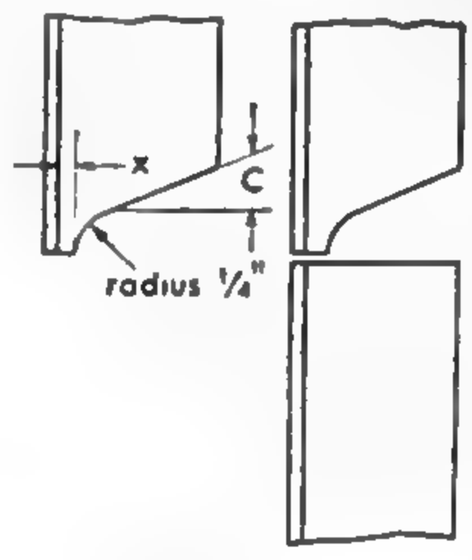
Table 4—Procedures for Welding Steel Side in the Horizontal Position



A
Single Vee



B
Single U



C
Single J

Root opening = 0 to $^1/_{16}$ In.; X = Root face = $^1/_{16}$ + $^1/_{32}$ − 0

Material Thickness, In.	Angle, deg. A	B	C	Single Vee Passes	Single Vee Elect. Diam., In.	Single U Passes	Single U Elect. Diam., In.	Single J Passes	Single J Elect. Diam., In.
1/4	45	..	..	1 2–3	1/8 5/32	..	...	..	...
3/8	45	..	..	1 2–3	1/8 5/32	..	...	..	...
1/2	40	..	30	1 2–5	5/32 3/16	..	...	1 2–4	5/32 3/16
3/4	30	22 1/2	30	1 2–15	5/32 3/16	1 2–10	5/32 3/16	1 2–7	5/32 3/16
1	30	22 1/2	30	1 2–21	5/32 3/16	1 2–15	5/32 3/16	1 2–11	5/32 3/16
1 1/4	30	22 1/2	30	1 2–27	5/32 3/16	1 2–21	5/32 3/16	1 2–16	5/32 3/16
1 1/2	..	22 1/2	30	..	...	1 2–28	5/32 3/16	1 2–22	5/32 3/16
1 3/4	..	22 1/2	30	..	...	1 2–36	5/32 3/16	1 2–29	5/32 3/16
2	..	..	30	..	...	..	...	1 2–37	5/32 3/16

Plate Thickness, In.	Width of Groove, In. 10% Clad	20% Clad
3/16 to 1/2	1/4	5/16
9/16 to 1	3/8	1/2
1 and up	1/2	5/8

The edges or shoulders of the groove should have generous radii to permit proper fusion, to prevent entrapment of slag and to overcome undercuts of the clad surface. For horizontal welds the bottom edges of the groove can be squared off to give an adequate shelf.

Welding Clad Side.—The clad side of the joint is welded last using the elec-

trodes recommended for the different types of cladding (see Table 6).

Selection of electrodes for the clad side is of prime importance in order to maintain continuity of corrosion-resistant surface. In addition, the welded joint must have the required strength. Certain elements are lost in the arc, and the transfer efficiency of oxidizable elements depends on the electrode coating. Both lime and titania coatings are available for the straight-chromium and chromium-nickel stainless steels, but lime has a better recovery rate than titania. Approximate loss of elements during welding with stainless electrodes is illustrated below.

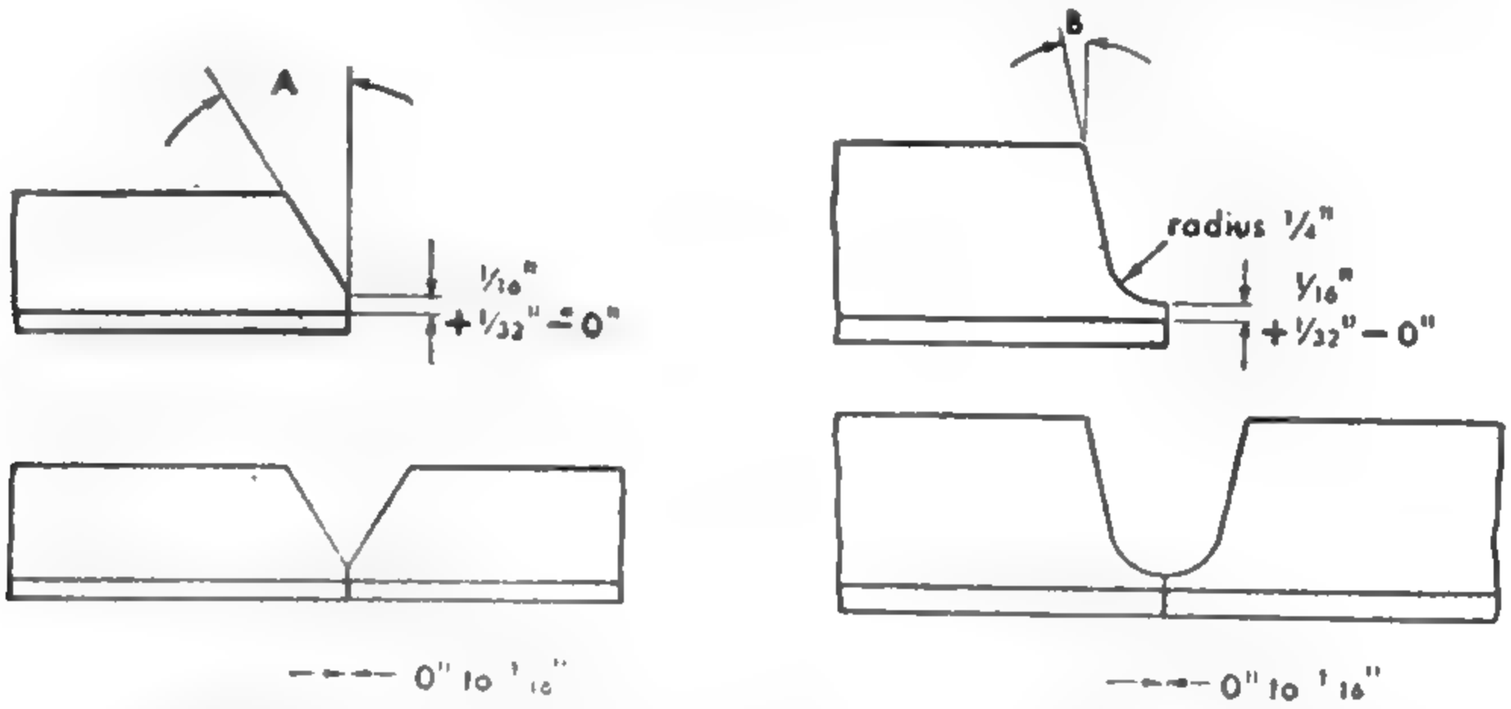
Element	% in Electrode	% in Weld Metal
Chromium	19.00	17–18.00
Nickel	9.00	9.00
Columbium	1.30	0.90–0.95

These figures for the 18–8 type steels must be regarded as typical examples, as the rate of transfer may change due to current, speeds, electrode coating and other factors.

Current and Voltage.—Narrow ranges of current and voltage are required for alloy electrodes. These ranges are critical and the recommendations of the manufacturer should be followed. The current ranges listed (Table 7) may not cover all the brands of high-alloy electrodes produced, but will serve satisfactorily as a guide for most of them. The higher limits of the range should be used in the flat or horizontal position, while the lower side of the range applies in the vertical and overhead positions.

Because of the high electrical resistance of alloy wire, electrodes become white hot if excessive currents are used. This will cause the coating of the electrode to flake off and porous welds will result. If the current is too low, the metal freezes before complete slagging has taken place,

Table 5—Procedures for Welding Steel Side in Vertical Position



Single Vee — Single U

Material Thickness, In	Angle, deg. A	Angle, deg. B	Single Vee: Passes	Single Vee: Elect. Diam., In.	Single U: Passes	Single U: Elect. Diam., In.
1/4	45	.	1	1/8	..	...
			2	5/32		
3/8	45	..	1	1/8	..	...
			2–3	5/32		
1/2	45	.	1	1/8	..	...
			2–3	5/32		
3/4	35	10	1	1/8	1	1/8
			2–4	3/16	2–4	3/16
1	30	10	1	5/32	1	5/32
			2–8	3/16	2–5	3/16
1 1/4	30	10	1	5/32	1	5/32
			2–10	3/16	2–6	3/16
1 1/2	..	10		...	1	5/32
					2–8	3/16
1 3/4	.	10	..	...	1	5/32
					2–10	3/16
2		10		.	1	5/32
					2–12	3/16

or lack of penetration may result. The voltage range is restricted, and a short arc should be held to conserve the oxidizable elements.

Table 6—Welding Electrodes—Clad Side

Cladding Type	Cover Exposed Steel with 1st Pass or Layer	Complete Balance of Weld with	Alloy to Steel (Welds Not Exposed to Corrosion)
405	25–20, 25–12, 18Cr[a]	25–20, 25–12, 18Cr[a]	25–20, 25–12
410	25–20, 25–12, 18Cr[a]	25–20, 25–12, 18Cr[a]	25–20, 25–12
14–16Cr	25–20, 25–12, 28Cr[a]	25–20, 25–12, 18Cr[a]	25–20, 25–12
430	25–20, 25–12, 28Cr[a]	25–20, 25–12, 18Cr[a]	25–20, 25–12
301	25–20, 25–12	25–20, 25–12, 19–9	25–20, 25–12
302	25–20, 25–12	25–20, 25–12, 19–9	25–20, 25–12
304	25–20, 25–12	25–20, 25–12, 19–9	25–20, 25–12
308	25–20, 25–12	25–20, 25–12, 19–9	25–20, 25–12
321	25–20Cb, 25–12Cb	25–20Cb, 25–12Cb, 19–9Cb	25–20, 25–12, 25–20Cb, 25–12Cb
347	25–20Cb, 25–12Cb	25–20Cb, 25–12Cb, 19–9Cb	25–20, 25–12, 25–20Cb, 25–12Cr
309	25–20	25–20	25–20, 25–12
310	25–20	25–20	25–20, 25–12
316	25–20Mo, 25–12Mo	25–20Mo, 25–12Mo, 19–9Mo	25–20, 25–12, 25–20Mo, 25–12Mo
"L" Nickel	Monel[c]	Nickel	Nickel 80Ni–20Cr, 25–20Cb, 25–12Cb
Nickel	Nickel, 80Ni–20Cr[b]	Nickel, 80Ni–20Cr[b]	Nickel 80Ni–20Cr, 25–20, 25–12
Monel	Nickel	Monel	Nickel
Inconel	80Ni–20Cr	80Ni–20Cr	80Ni–20Cr, 25–20, 25–12

[a] Must be used under certain corrosive conditions.
[b] May be used under certain corrosive conditions.
[c] When special electrodes are not available, a nickel root layer should be deposited.

Alloy electrodes are generally used with d.c., reverse polarity (electrode positive-work negative). This results in faster melting of the electrode and less heat input into the steel backing plate, avoiding excessive penetration of the backing material. High-alloy a.c. electrodes are also available.

Table 7—Recommended Current Ranges for Alloy Electrodes, Amp.

Electrode Diameter, In.	Chromium Steel and Pure Nickel	Chromium-Nickel Steel and Monel	Inconel and 80 Nickel-20 Chromium Steel
1/8	90–130	70–105	80–100
5/32	125–170	100–140	110–140
3/16	160–210	130–180	140–160
1/4	200–300	240–400	.....

Straight Chromium Cladding

Some corrosive conditions may require welding a straight chromium cladding with straight chromium electrodes. Contamination or dilution of the weld metal by pick-up of the backing steel may be eliminated or guarded against by the use of an electrode containing higher chromium than the cladding material, or by using a number of successive, thin layers of the same analysis as the cladding. (Fig. 10 shows welding procedures.)

It is general practice to weld straight-chromium-clad materials with an austenitic electrode in order to eliminate the brittle characteristics of straight chromium weld metal. Austenitic chromium-nickel electrodes of the 25–20 or 25–12 analysis are normally used. This type electrode eliminates the hard, brittle structure and the large grain size encountered in straight chromium weld metal. However, it does not eliminate the brittle structure in the heat-affected zones of the base plate. A stabilized austenitic electrode should be used if the weldment is to operate in the carbide precipitation temperature range, or if stress-relief heat treatment is required. Austenitic electrodes have a 40 to 60% higher coefficient of thermal expansion than straight chromium material, and the location of joints and the nature of restraint should be given consideration when the weldment is to operate over a wide range of temperatures. The possibility of galvanic action due to the presence of a more noble metal should also be considered from a corrosion standpoint. (Figure 11 shows welding procedures to be used.)

Type 405.—This material has a small percentage of aluminum added to alleviate the air-hardening tendencies of the basic alloy. Preheating is not required unless heavy gages are to be welded.

Types 410 Modified and 430 Modified.—These materials are somewhat brittle in the as-welded condition. Type 410 has pronounced air-hardening characteristics unless of the low-carbon grade. Type 430 has a tendency toward brittleness

associated with grain growth. These materials may be preheated to 300–400°F., and should be held at that temperature range during welding. Such preheating may be done at the weld zone, the weldment being stress relieved immediately following welding and prior to cooling.

Austenitic Cladding.

Consideration of dilution or contamination of alloy weld metal caused by pick-up of iron from the steel backing plate is important from a corrosion standpoint. Dilution can be controlled by using a higher alloy electrode than the cladding alloy or by depositing thin layers of the same alloy as the cladding. The most common procedure is to deposit the root bead with 25–20 or 25–12 electrodes and to complete the weld with electrodes of the same composition as the cladding. (Figures 12 and 13 show welding procedures to be used.)

Types 301 and 302.—Because of the high-carbon content and the danger of carbide precipitation, these materials are seldom used for severely corrosive conditions. However, they are often employed for architectural or decorative purposes where corrosive conditions are not severe. As these applications are generally in the lighter gage materials, it is customary to weld them with a 25–20 or 25–12 electrode throughout their composite thickness.

Type 304 Modified and Type 308.—These materials are usually welded with a root pass of 25–20 or 25–12, followed by succeeding deposited layers of 19–9 electrodes.

Types 321 and 347 Modified.—These materials are welded with columbium-bearing electrodes, as titanium is oxidized in the welding arc. The root pass is generally made with a 25–20 Cb or 25–12 Cb electrode, followed by layers of 19–9 Cb. Due to crack sensitivity sometimes found with the 25–20 Cb or 25–12 Cb, in some cases a root pass of 25–12 or 25–20 is used before depositing metal from a stabilized electrode.

Type 309.—This material is welded throughout with 25–20 electrodes (see Fig. 13).

Type 310.—This material, in light cladding thicknesses, is welded throughout with 25–20 electrodes. As a result of dilution, half the thickness of the root bead must be ground off before the succeeding layers are deposited (see Fig. 13).

Type 316 Modified.—It is customary to make the root pass of this material with 25–20 Mo or 25–12 Mo electrodes and succeeding layers with 19–9 Mo electrodes. When severely corrosive conditions are to be encountered or stress-relief treatment is to be given, Type 316 with 0.03% max. carbon or Type 316 columbium-stabilized clad material should be used with electrodes containing molybdenum.

Nickel.—Nickel is one of the few pure metals commonly used for cladding. (See Fig. 14 for welding procedures to be used.) Under certain corrosive conditions the iron content of the nickel weld must be held to extremely low values. However, in the majority of applications, a severe limitation on iron content is not required as the nickel-iron solid solutions are sufficiently corrosion-resistant.

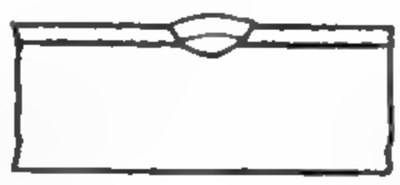
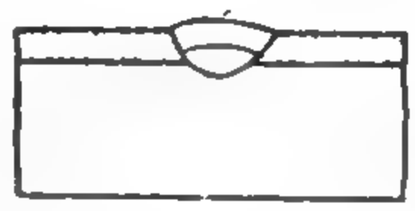
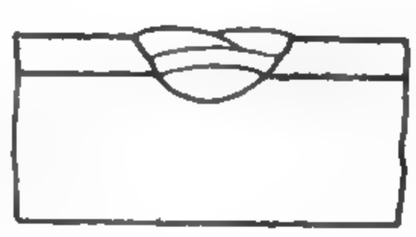
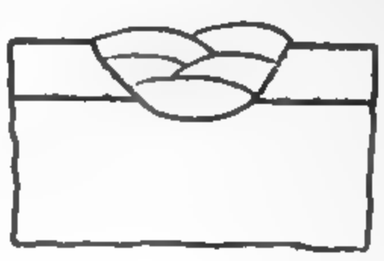
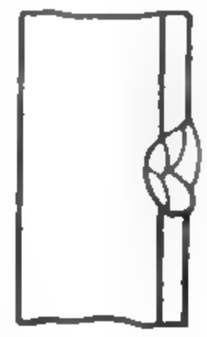
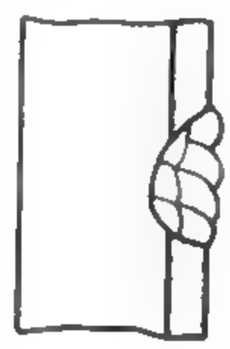
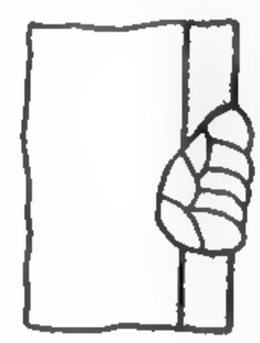
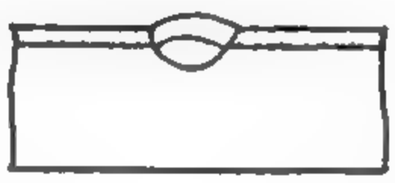
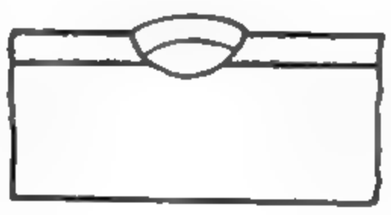
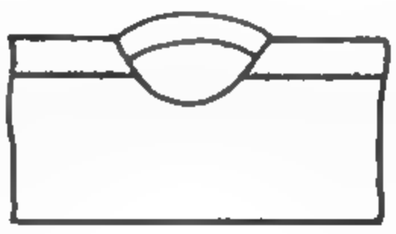
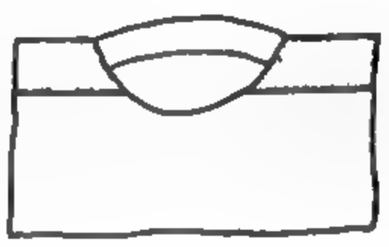
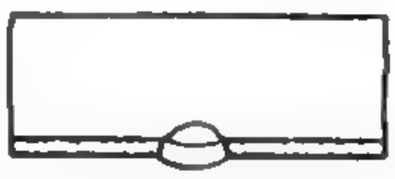
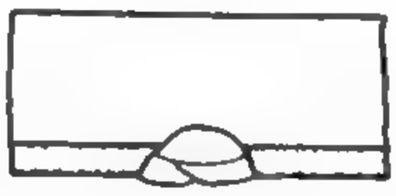
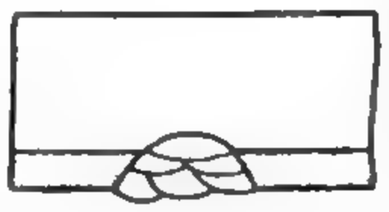
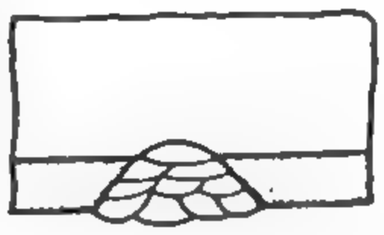
Stringer beads from small diameter electrodes should be used. Where iron pick-up is to be held to a minimum, the top half of the root bead should be chipped or ground off before the succeeding layers of weld metal are deposited. The greater the number of layers of nickel weld metal, the lower the iron content will be in the top layer of weld metal.

The 80 nickel–20 chromium electrodes are used under certain corrosive conditions to weld steels with a nickel cladding, as the chromium compensates for iron pick-up and the weld is cathodic to the nickel surface. The 80–20 alloy plus iron on steels with a nickel cladding produces a composition similar to Inconel (78 Ni, 14 Cr, 6 Fe). (See Fig. 15 for welding procedures to be used.)

Inconel.—All weld layers should be deposited with 80 nickel–20 chromium electrodes to compensate for iron pick-up or dilution (see Fig. 15).

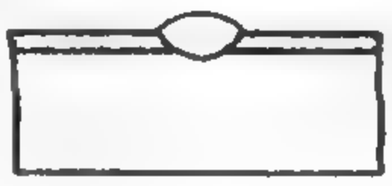
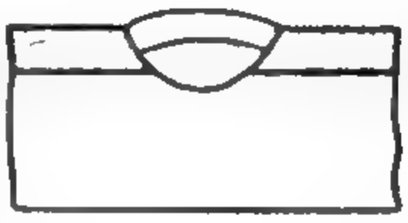
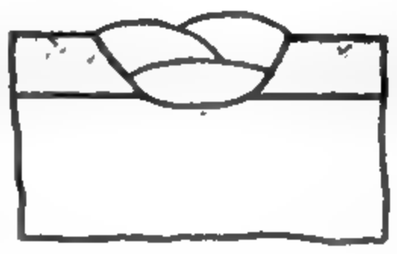
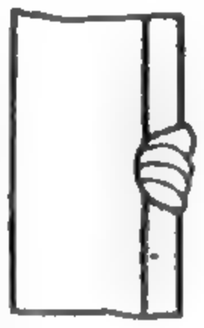
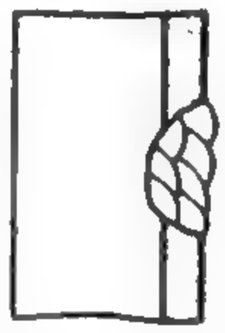
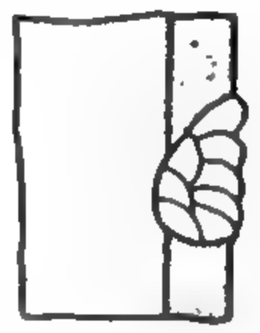
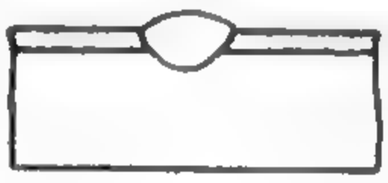
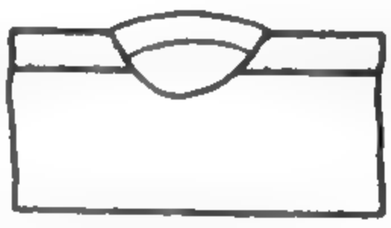
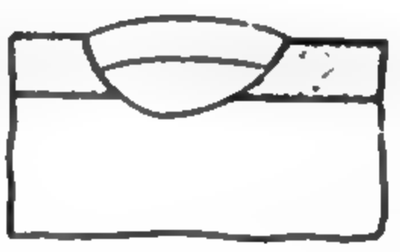
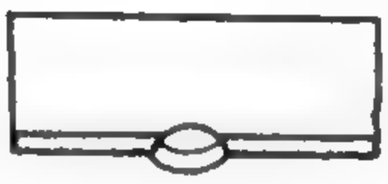
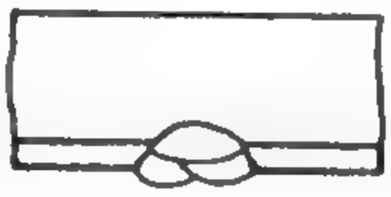
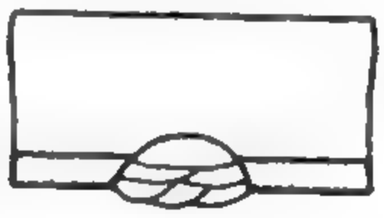
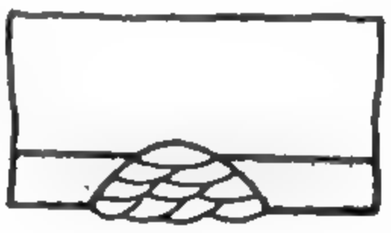
Monel.—The Monel side of Monel-clad steel should be welded with a Monel electrode specifically developed for that purpose, or for the overlaying of Monel on steel. If the special electrode is not available, an underlayer of nickel must be employed to cover the steel exposed by chipping or grinding as otherwise a hot-short or brittle condition might result from the formation of a copper-iron alloy. (See Fig. 16 for welding procedures to be used.)

Cupro-Nickel.—This material is commonly welded with a 70 nickel–30 copper electrode using multiple layers to over-

Position	1/4 to 1/2 incl. 10% clad	1/4 to 1/2 incl. 20% clad 9/16 to 1 incl. 10% clad	9/16 to 1 incl 20% clad 1 1/8 and up 10% clad	1 1/8 and up 20% clad
Flat				
Passes	1 2	1 & 2	1 to 4	1 to 5
Elect. Diam.	1/8 1/8 – 5/32	5/32	5/32	5/32
Horizontal				
Passes	1 to 4	1 to 2 3 to 4 or 5	1 to 3 4 to 6 or 7	1 to 7 or 8
Elect. Diam.	1/8	1/8 5/32	1/8 5/32	5/32
Vertical				
Passes	1 2	1 & 2	1 & 2	1 & 2
Elect. Diam.	1/8 1/8 or 5/32	5/32	5/32	5/32
Overhead				
Passes	1 & 2	1 to 3	1 to 6	1 to 10
Elect. Diam.	1/8	5/32	5/32	5/32

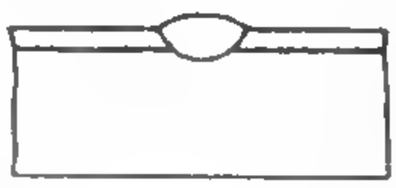
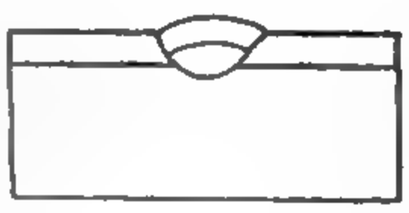
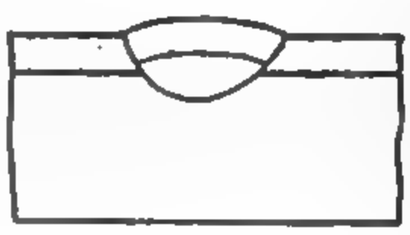
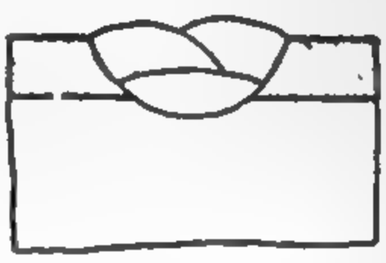
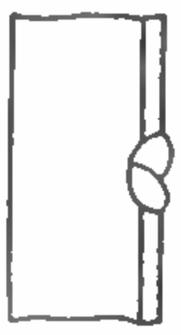
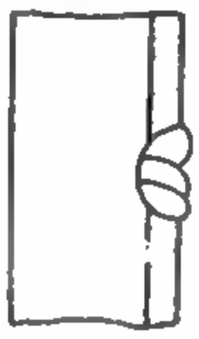
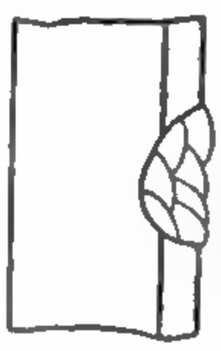
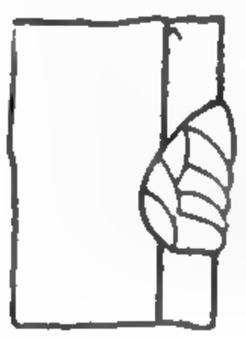
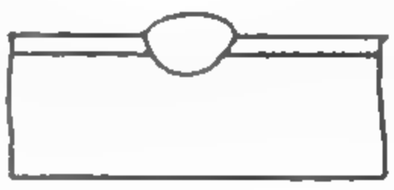
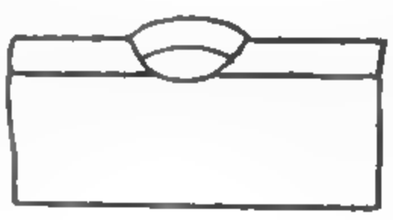
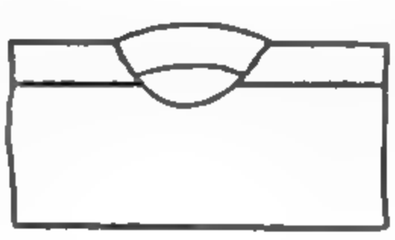
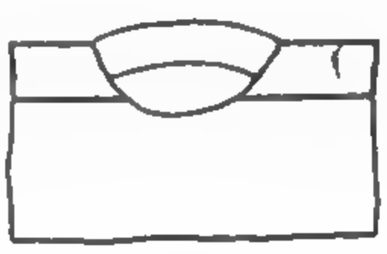
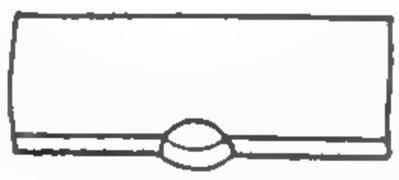
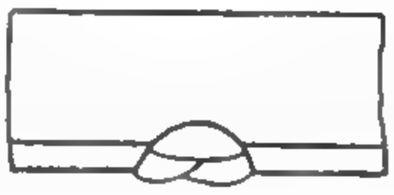
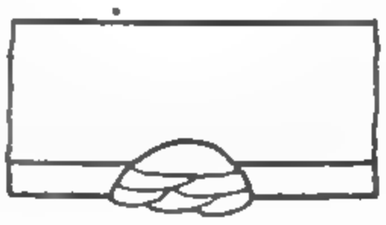
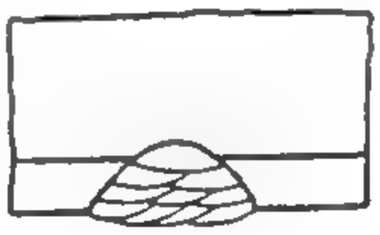
NOTE: Root layer should be ground in multiple-pass welds.

Fig. 10.—Procedures for Welding Straight Chromium Cladding with Straight Chromium Steel Electrodes

Position	1/4 to 1/2 incl. 10% clad	1/4 to 1/2 incl. 20% clad 9/16 to 1 incl. 10% clad	9/16 to 1 incl. 20% clad 1 1/8 and up 10% clad	1 1/8 and up 20% clad
Flat				
Passes	1	1 & 2	1 2	1 2 & 3
Elect. Diam.	5/32	5/32	5/32 3/16	5/32 3/16
Horizontal				
Passes	1 & 2	1 to 4	1 to 7	1 to 3 4 to 8
Elect. Diam.	5/32	5/32	5/32	5/32 5/32 or 3/16
Vertical				
Passes	1	1 & 2	1 & 2	1 & 2
Elect. Diam.	5/32	5/32	5/32	5/32
Overhead				
Passes	1 & 2	1 to 3	1 to 6	1 to 10
Elect Diam.	1/8	5/32	5/32	5/32

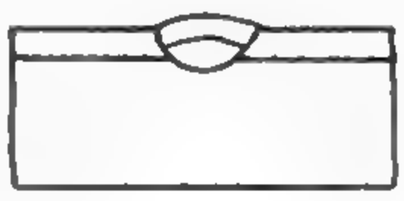
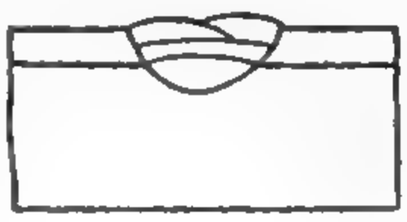
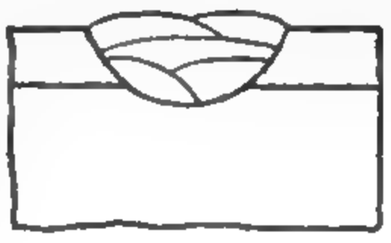
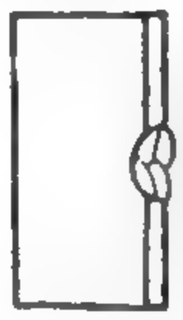
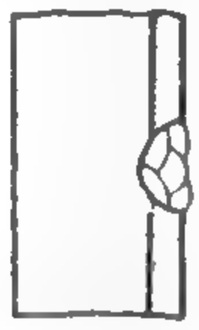
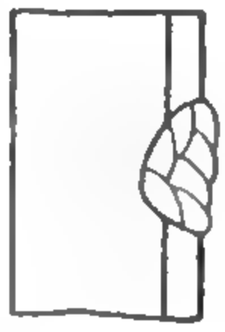
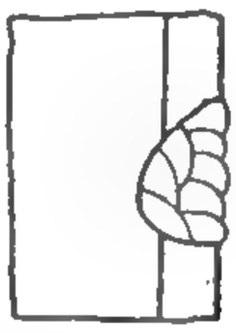
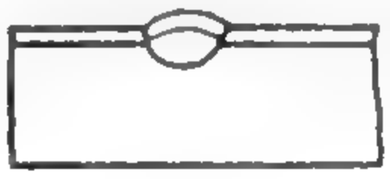
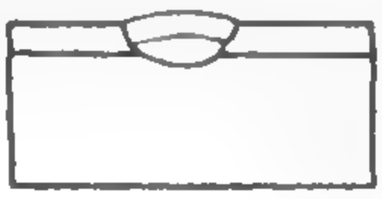
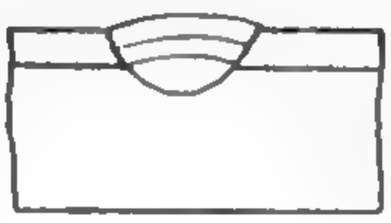
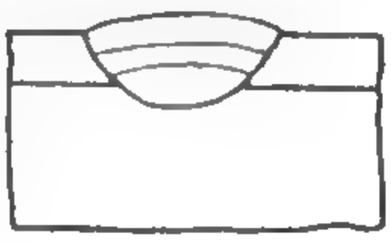
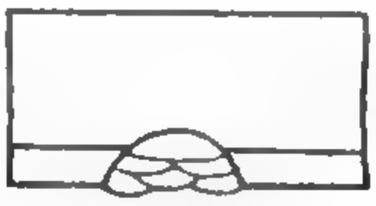
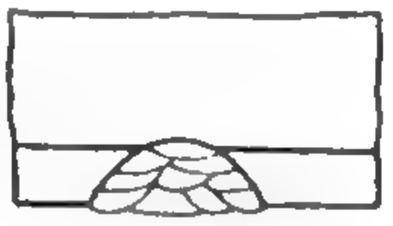
NOTE: Root layer should be ground in multiple-pass welds.

Fig. 11.—Procedures for Welding Straight Chromium Steel Cladding with Austenitic Cr-Ni Stainless Electrodes

Position	1/4 to 1/2 incl 10% clad	1/4 to 1/2 incl. 20% clad 9/16 to 1 incl 10% clad	9/16 to 1 incl 20% clad 1 1/8 and up 10% clad	1 1/8 and up 20% clad
Flat				
Passes	1	1 & 2	1 2	1 2 & 3
Elect. Diam.	5/32	5/32	5/32 3/16	5/32 3/16
Horizontal				
Passes	1 & 2	1 to 3	1 to 7	1 to 3 4 to 8
Elect. Diam.	5/32	5/32	5/32	5/32 5/32 or 3/16
Vertical				
Passes	1	1 & 2	1 & 2	1 & 2
Elect. Diam.	5/32	5/32	5/32	5/32
Overhead				
Passes	1 & 2	1 to 3	1 to 6	1 to 10
Elect. Diam.	1/8	5/32	5/32	5/32

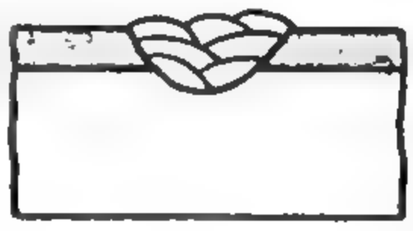
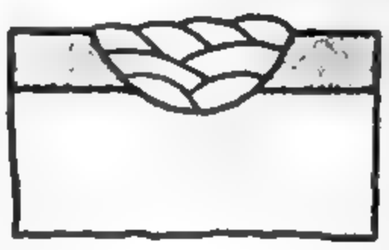
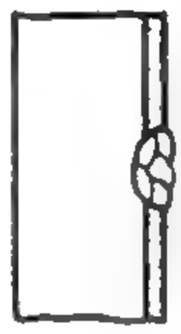
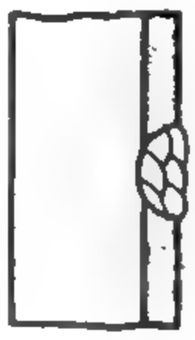
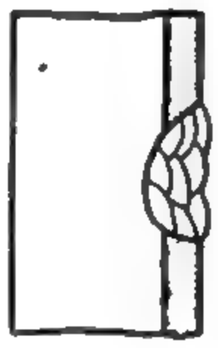
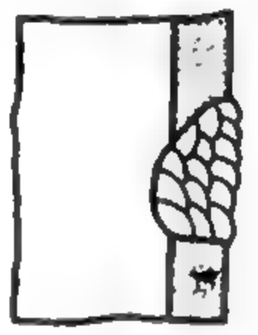
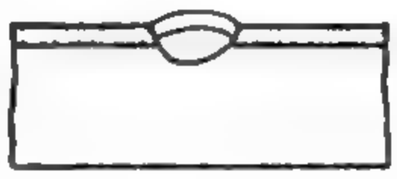
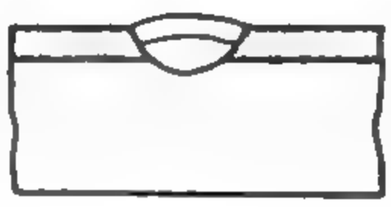
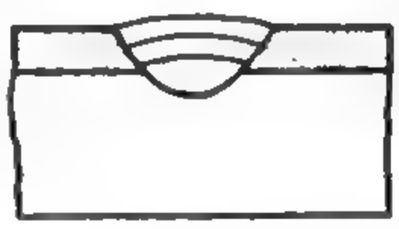
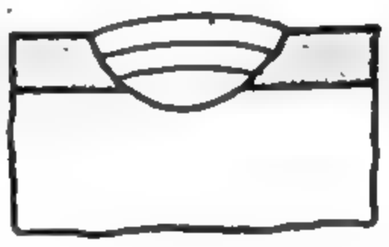
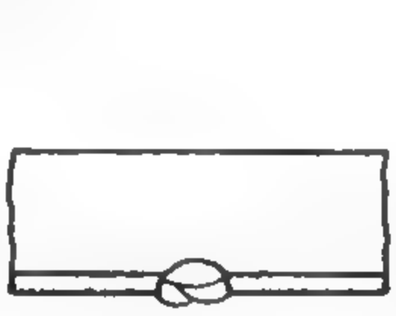
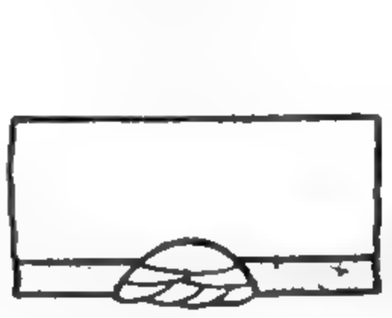
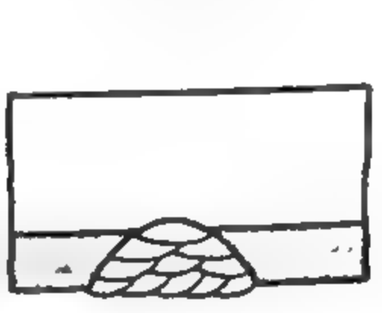
NOTE: Root layer should be ground in multiple pass welds.

Fig. 12.—Procedures for Welding 18–8 Claddings with 25–20 or 25–12 Cr-Ni Electrodes

Position	1/4 to 1/2 incl. 10% clad	1/4 to 1/2 incl. 20% clad 9/16 to 1 incl. 10% clad	9/16 to 1 incl. 20% clad 1 1/8 and up 10% clad	1 1/8 and up 20% clad
Flat				
Passes	1 & 2	1 2	1 to 4	1 & 2 3 to 5
Elect. Diam.	1/8	1/8 5/32	5/32	5/32 3/16
Horizontal				
Passes	1 to 4	1 & 2 3 to 5	1 to 7 or 8	1 to 3 4 to 8
Elect. Diam.	1/8	1/8 5/32	5/32	5/32 5/32 or 3/16
Vertical				
Passes	1 2	1 & 2	1 to 3	1 to 3
Elect. Diam.	1/8	5/32	5/32	5/32
Overhead				
Passes	1 & 2	1 to 3	1 to 6	1 to 10
Elect. Diam.	1/8	5/32	5/32	5/32

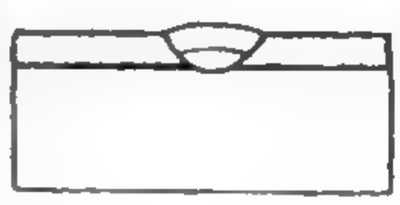
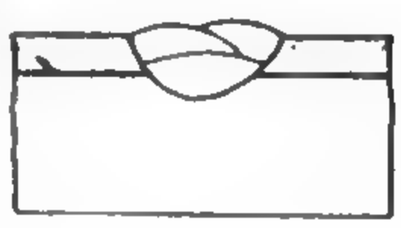
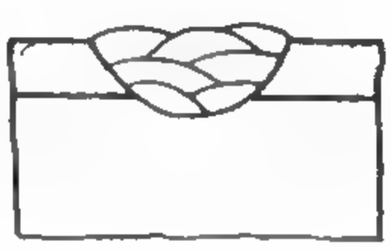
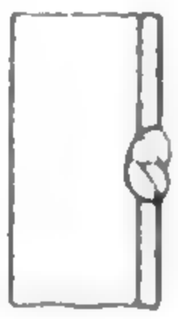
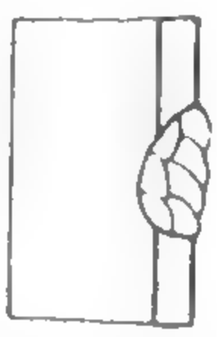
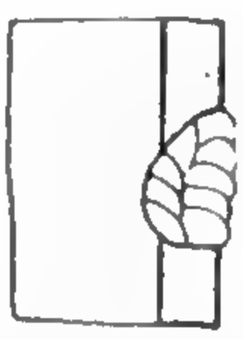
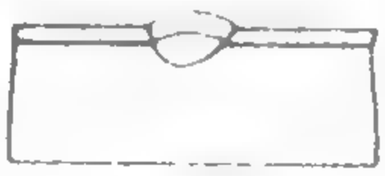
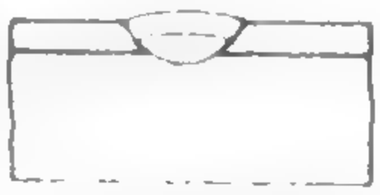
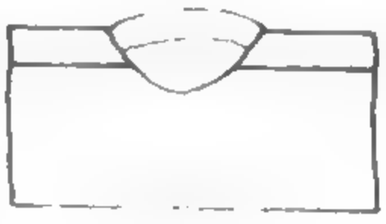
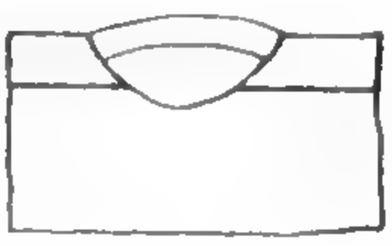
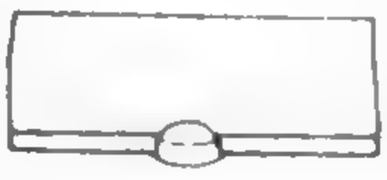
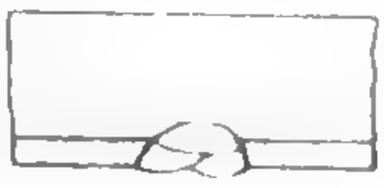
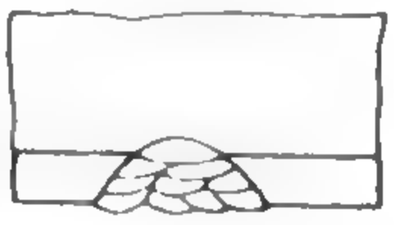
NOTE: Root layer should be ground in multiple pass welds.

Fig. 13.—Procedures for Welding 25–12 or 25–20 Claddings with 25–20 Electrodes

Position	1/4 to 1/2 incl. 10% clad	1/4 to 1/2 incl. 20% clad 9/16 to 1 incl. 10% clad	9/16 to 1 incl. 20% clad 1 1/8 and up 10% clad	1 1/8 and up 20% clad
Flat				
Passes	1 to 3	1 to 4	1 & 2 4 to 7	1 to 8
Elect. Diam.	1/8	1/8	1/8 5/32	5/32
Horizontal				
Passes	1 to 4 or 5	1 to 5 or 6	1 to 9	1 to 15 or 16
Elect. Diam.	1/8	1/8	1/8	1/8
Vertical				
Passes	1 & 2	1 & 2	1 to 3	1 to 3
Elect. Diam.	1/8	1/8	1/8	1/8
Overhead				
Passes	1 to 3	1 to 6	1 to 7	1 to 11
Elect. Diam.	1/8	5/32	5/32	5/32

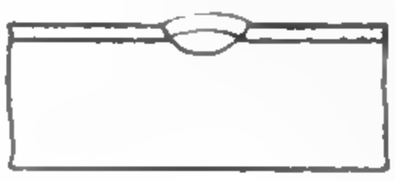
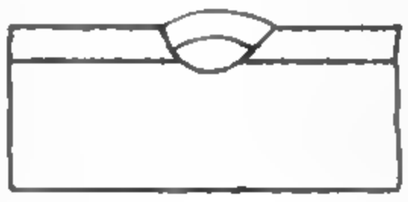
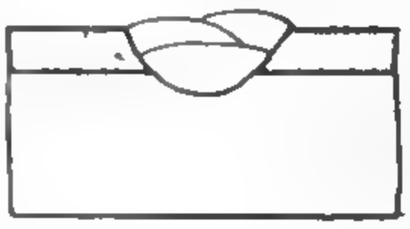
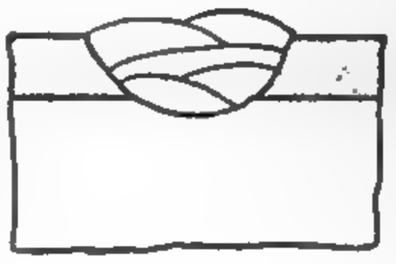
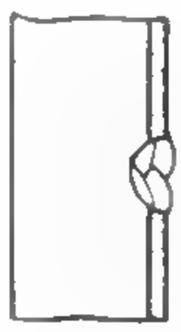
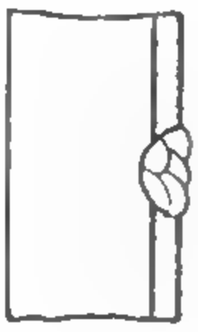
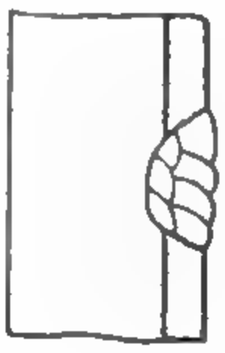
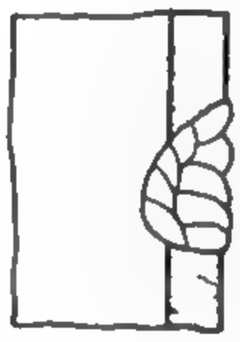
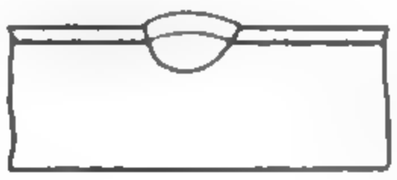
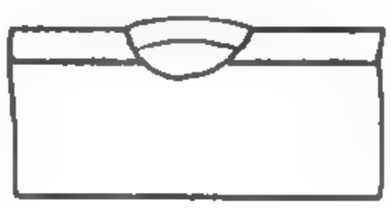
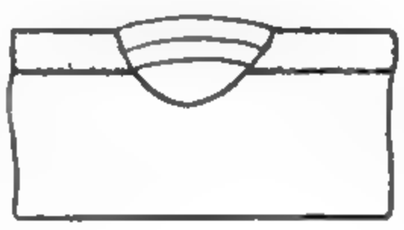
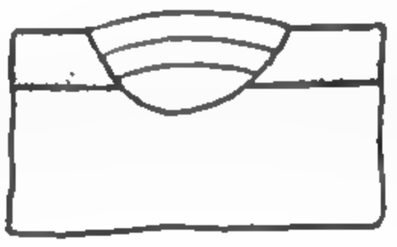
NOTE: Root layer should be ground in multiple pass welds.

Fig. 14.—Procedures for Welding Nickel Claddings with Nickel Electrodes

Position	1/4 to 1/2 incl. 10% clad	1/4 to 1/2 incl. 20% clad 9/16 to 1 incl. 10% clad	9/16 to 1 incl. 20% clad 1 1/8 and up 10% clad	1 1/8 and up 20% clad
Flat				
Passes	1 & 2	1 2	1 2 & 3	1 & 2 3 to 7
Elect. Diam.	1/8	1/8 5/32	1/8 5/32	1/8 5/32
Horizontal				
Passes	1 to 4	1 & 2 3 to 5	1 to 3 4 to 7	1 to 4 5 to 9
Elect. Diam	1/8	1/8 5/32	1/8 5/32	1/8 5/32
Vertical				
Passes	1 & 2	1 2	1 & 2	1 & 2
Elect. Diam.	1/8	1/8 5/32	5/32	5/32
Overhead				
Passes	1 & 2	1 to 3	1 to 6	1 to 10
Elect. Diam.	1/8	5/32	5/32	5/32

NOTE Root layer should be ground in multiple pass welds

Fig. 15.—Procedures for Welding Nickel or Inconel Claddings with Nickel-Chromium Electrodes

Position	1/4 to 1/2 incl 10% clad	1/4 to 1/2 incl. 20% clad 9/16 to 1 incl. 10% clad	9/16 to 1 incl. 20% clad 1 1/8 and up 10% clad	1 1/8 and up 20% clad
Flat				
Passes	1 & 2	1 2	1 to 3	1 & 2 3 to 6.
Elect. Diam.	1/8	1/8 5/32	5/32	5/32 5/32 or 3/16
Horizontal				
Passes	1 & 2 3 & 4	1 & 2 3 to 5	1 to 3 4 to 7	1 to 4 5 to 9
Elect. Diam.	1/8 5/32	1/8 5/32	1/8 5/32	1/8 5/32
Vertical				
Passes	1 & 2	1 2	1 to 3	1 to 3
Elect. Diam.	1/8	1/8 5/32	5/32	5/32
Overhead				
Passes	1 & 2	1 2 & 3	1 to 6	1 to 11
Elect. Diam.	1/8	1/8 5/32	5/32	5/32

NOTE: When special electrodes are not available, a nickel root layer should be deposited.

Fig. 16.—Procedures for Welding Monel Claddings with Monel Electrodes

come iron pickup or dilution. Monel electrodes are used in many cases. The root pass should be made with nickel electrodes as in the case of Monel-clad.

Welding 3/16-In. Clad Steels.—The three methods commonly used to weld light-gage clad materials are detailed below. It is recommended that 20% cladding be specified for 3/16-in. material to provide sufficient cladding to give adequately corrosion-resistant welds. (For commercial fabrication, 0.030-in. cladding thickness is suggested as minimum.)

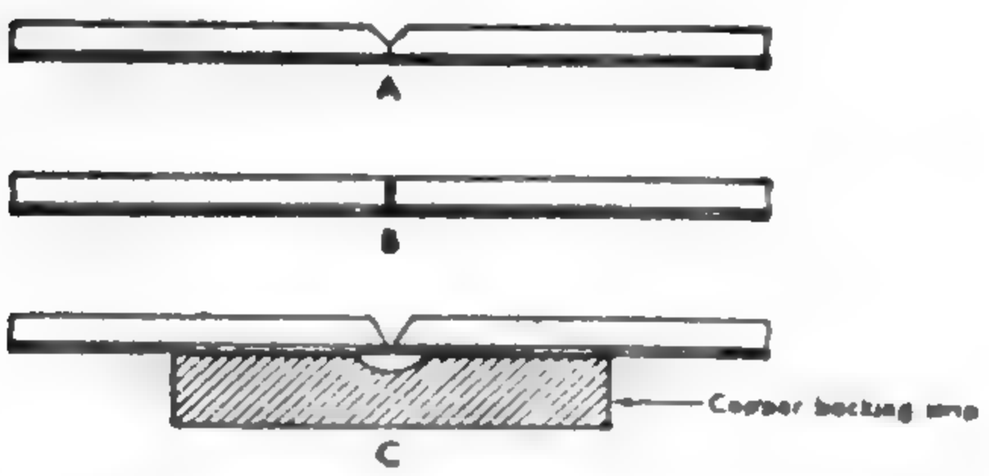


Fig. 17.—Edge Preparation for Welding 3/16-In. Clad Steel

Figure 17*A* illustrates the most commonly used edge preparation for welding light-gage material. The plate is beveled approximately 60 deg. on the steel side and is welded in the usual manner. Figure 17*B* illustrates the method used where unfused areas will not be detrimental. This type of joint is often used for tanks that are thoroughly braced or stayed. The plates should be fitted together tightly and the steel side should be welded first, using a 1/8- or 5/32-in. diam. E6012 or E6013 electrode to prevent excessive penetration. The clad side is then welded, using a 1/8-in. diam. alloy electrode at a rapid rate of travel.

Figure 17*C* illustrates the use of a copper backing strip for welding light-gage materials. The groove in the copper backing strip should be approximately 5/32-in. wide by 1/16-in. deep. The plates should be spaced with a 1/8-in. root opening and the joint welded throughout with a 1/8-in. diam. alloy electrode.

Blind Joints.—In many structures, joints are found that necessitate the welding of clad material throughout its composite thickness from one side only. Either of two methods may be used when this situation is encountered.

The use of a copper backing strip as shown in Fig. 18*A* is suggested when adequate clearance is available. When the clad surface is on the inaccessible side, it is necessary to weld the entire cross section of the joint with alloy electrodes. Root beads (thickness of the cladding) should be deposited using the electrodes listed in Table 6, Column 3. The balance of the weld should be completed using the electrodes listed in Table 6, Column 4. When the steel section is on the inaccessible side, steel welding electrodes may be used within 1/8 or 1/16 in. of the clad line and the joint may then be completed with an alloy electrode, as listed in Table 6, columns 2 and 3.

Backing strips are also used in the type of joint illustrated in Fig. 18*B*. When the clad material is on the inaccessible side, a backing strip of the same analysis as the cladding must be used. This strip is attached to one of the plates by a fillet weld and alloy weld metal deposited on this strip as noted above. In this case, alloy weld metal must be used throughout the joint. When the clad surface is exposed, a steel backing strip suffices and steel electrodes may be deposited within 1/16 or 1/8 in. of the cladding, followed by alloy electrodes as listed in Table 6.

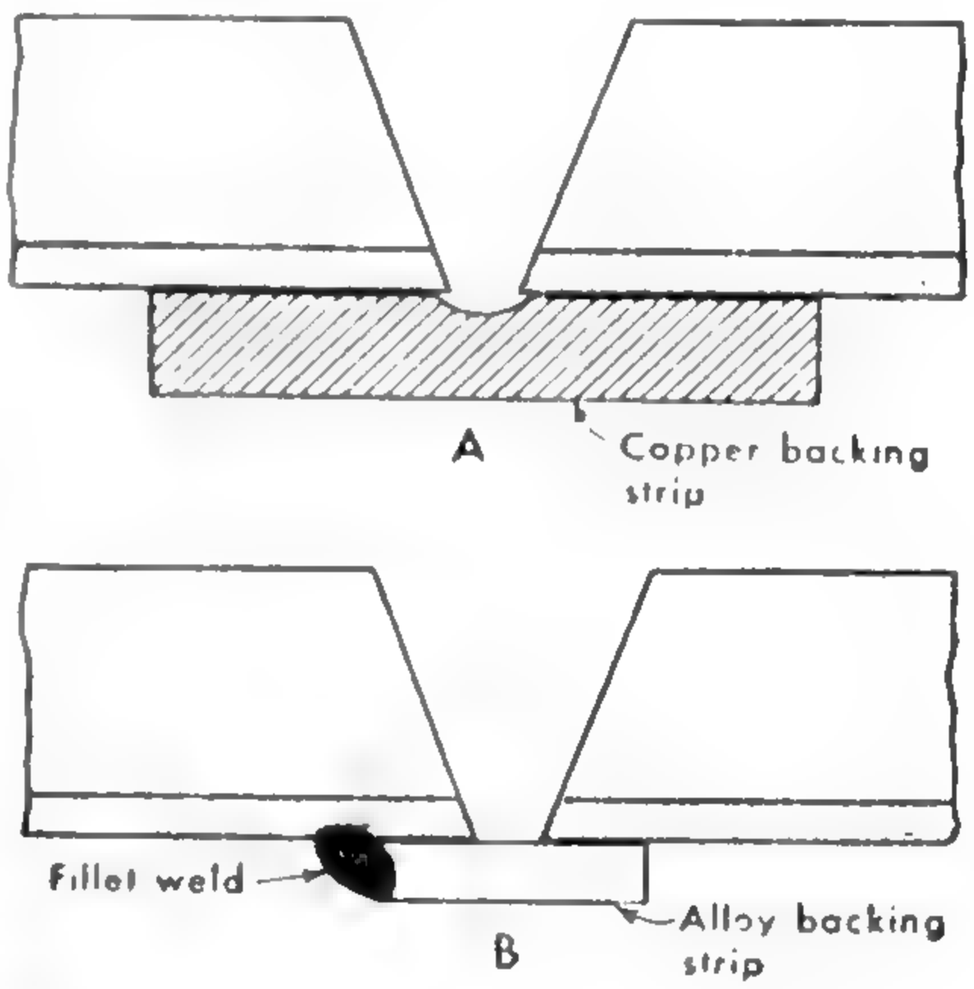


Fig. 18.—Edge Preparation for Blind Joints

Corner Joints.—Figure 19 illustrates various types of corner joints commonly encountered in clad steel fabrication. It is strongly suggested that whenever facilities and design permit, corner joints be eliminated and a formed section as shown in Fig. 19*E*, be used. This type of construction permits a butt joint which is

more desirable from both fabrication and structural standpoints. If this type of construction is used, the straight flange section should extend as far as possible beyond the corner so that adequate clearance is provided for manufacturing purposes. Table 6 indicates the proper type of electrode to use when welding the clad side of various corner joints.

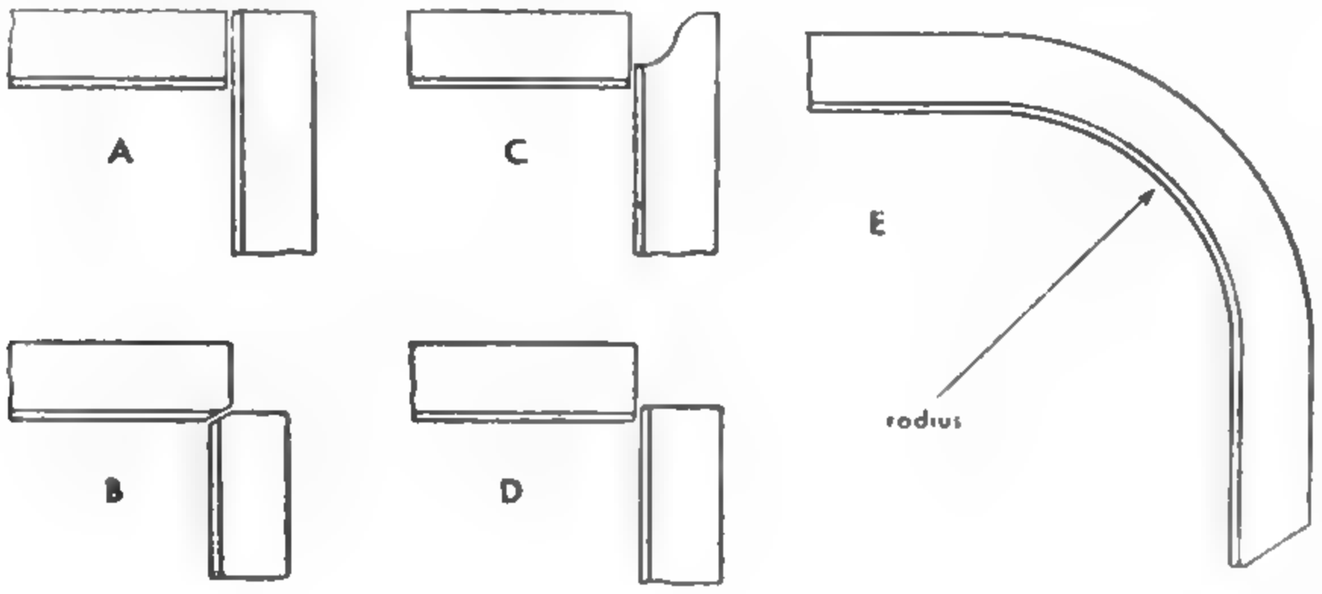


Fig. 19.—Typical Corner Joints for Clad Steels

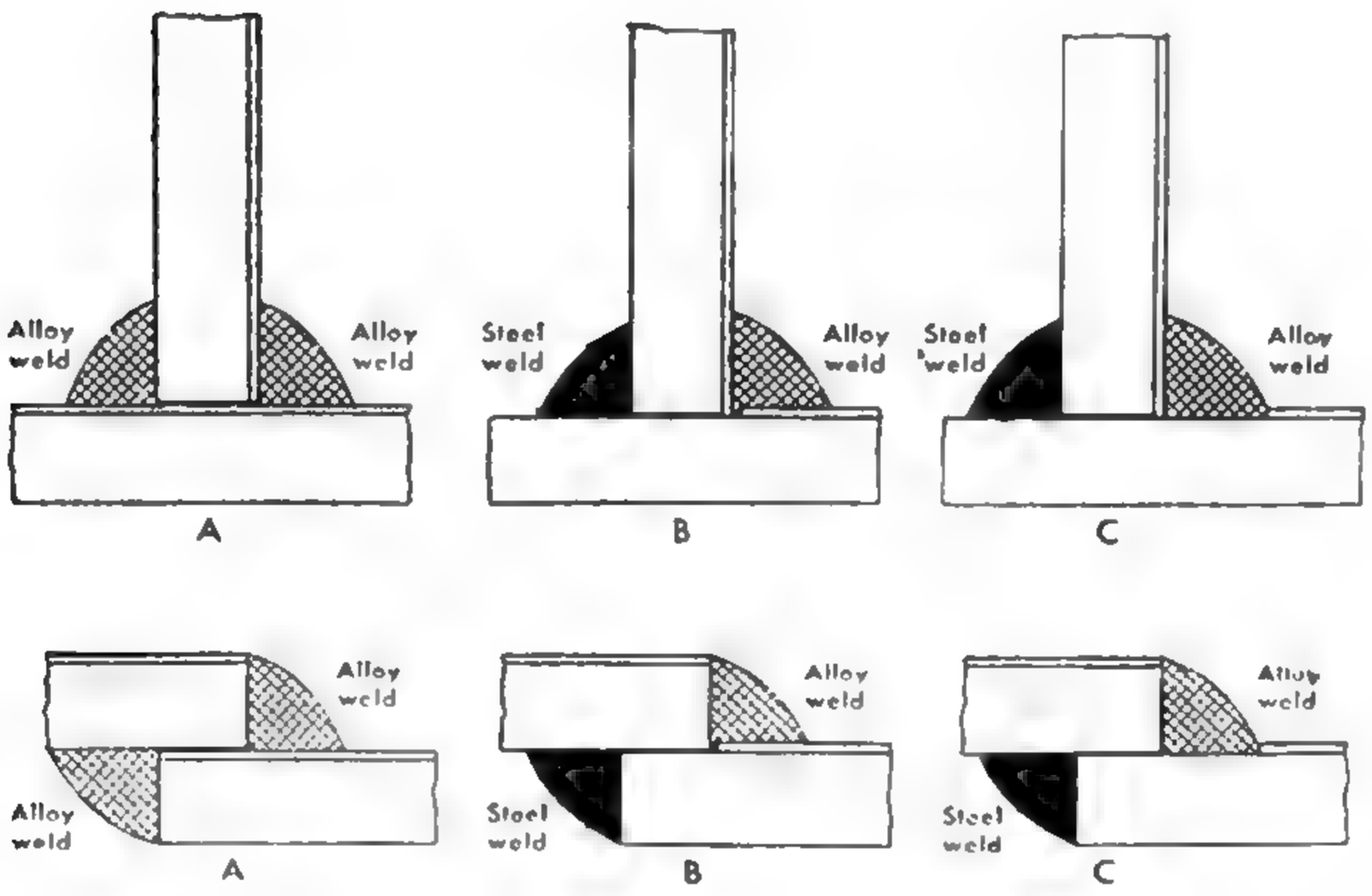


Fig. 20.—Typical Tee Joints for Clad Steels

Fig. 21.—Typical Lap Joints for Clad Steels

The type of joint shown in Fig. 19*A* can be used on unstressed or heavily supported structures. The outside should be welded with a large diameter steel electrode to dissipate and dilute the pickup of clad material. If desired, an alloy electrode may be used to weld the outside of the joint. The inside of the joint should be welded with the appropriate alloy electrode. This type of joint has an undesirable unfused area.

The type of joint shown in Fig. 19*B* may be welded in either of two ways. The clad side may be welded first with the appropriate alloy electrode, followed by back-chipping the outside and welding the balance of the joint with alloy electrodes.

The second method is to weld the steel side throughout with steel, back-chip from the inside and weld with the appropriate alloy electrode.

The types of joints shown in Figs. 19*C* and 19*D* should be welded throughout with alloy electrodes. After welding the clad side, the steel side should be back chipped or ground and welded with alloy electrodes.

Tee and Lap Joints.—The types of tee and lap joints commonly used in clad steel fabrication are shown in Figs. 20 and 21.

Double-Vee- or U-Groove Butt Joints.—When double-vee- or U-groove butt joints are used on heavy-gage clad materials, it is suggested that the center-line of the bevels be offset to favor the clad side as illustrated in Fig 22. This will result in the use of lower amounts of alloy weld metal.

Welding Double-Clad Steels

Two methods are in general use for welding double-clad steels.

The first and more commonly used method is to use the standard vee or U groove as encountered when welding

single-clad material. The steel portion is welded with the appropriate steel electrodes within approximately $^1/_{16}$ to $^1/_8$ in. of the clad line, followed by welding with corrosion-resistant material. The unwelded clad surface is then back chipped and welded in the same manner as a single-clad plate.

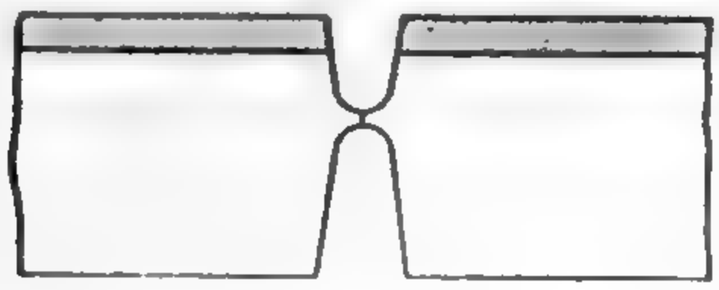


Fig. 22.—Edge Preparation for Double-U Groove Weld

On heavy-gage plates a double-vee or U preparation can be used. The steel section may be welded with the appropriate steel electrodes within $^1/_{16}$ to $^1/_8$ in. of the clad line. The balance of the joint can then be completed with the appropriate corrosion-resistant electrodes.

Cover Strips for Clad Welds

Strips of corrosion-resistant metal are occasionally applied over welded joints on the clad side as an added protection for some corrosive service (see Fig. 23). The lining material should be of the same type as the cladding. The minimum lining thickness should be 0.050 in. in the interest of fitting and welding. Thickness of the strip should never be less than the thickness of cladding. Exact thickness and size depend on design and the nature of service. For welding electrodes, refer to Table 6, Column 3.

Arc Welding.—For strips up to 0.150-in thick, $^1/_8$-in. diam. electrodes should be used, while $^5/_{32}$-in. diam. electrodes may be used with thicker strips. Welding procedures should provide the minimum adequate penetration of weld metal into exposed steel or clad material. Weld metal analyses or welding procedure should be such as to compensate for any dilution.

Inert-Gas Metal-Arc Welding.—Use of argon or helium-shielded metal-arc welding has been limited to application of strip covers over welded clad joints. This technique may be used on all clad materials except nickel, but care must be taken to provide minimum, but adequate, penetration. The weld may be made without addition of filler metal in most cases. High purity helium must be used on Monel claddings.

Overlays of Alloy on Ferrous Material

In general, overlays of alloys on ferrous material cover small areas such as flanges and nozzle faces. Welding conditions must provide adequate but minimum penetration of the alloy weld metal in the steel. The first layer of alloy should be applied with a $^1/_8$-in. diam. electrode at normal amperage. Dilution can be controlled by directing the arc against the back of the weld. For Monel, an interlayer of nickel weld metal is recommended, when special electrodes developed for this type of work are not available. The second and succeeding layers may be applied, using $^1/_8$-in. or $^5/_{32}$-in. diam. electrodes, depending on the area to be covered and thickness of backing metal. Analyses of electrodes used are shown in Table 6.

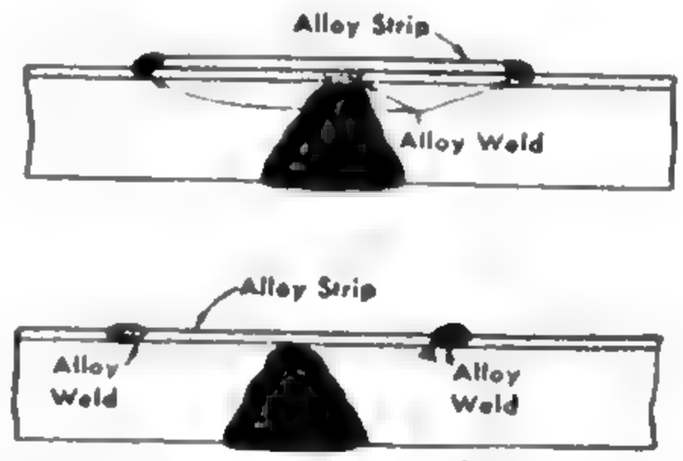


Fig. 23.—Cover Strips for Clad Plates

Submerged Arc Welding.—Care must be taken in selection of proper welding conditions to insure successful fabrication of clad steels by submerged arc welding. This type of welding can penetrate deeply and fuse a large portion of base metal to mix it with welding electrode. This fact must be given consideration in welding both steel and alloy sides of clad material.

Backing steel for submerged-arc welding should be fully killed material, such as ASTM A-201, to produce satisfactory welding with the high heat input employed with this process.

Extreme care must be taken to prevent any penetration of steel weld metal into the cladding. The plate should be given the conventional preparation on the steel side, with the exception that a root face of $^3/_{32}$-in. min. thickness should be left above the surface of the cladding. One or two beads of steel weld metal should be deposited manually to provide a back-

ing for the submerged-arc weld and to prevent penetration of the cladding with resulting alloy pickup.

As an alternative, the plate may be prepared with the conventional groove for automatic welding and the cladding may be stripped back not less than 1/4 in. on each side. A large root face of steel must be provided for backing of the automatic weld.

When welding the clad side, the groove should be chipped, ground or machined down to clean, sound steel weld metal. Width and depth of this groove should be held to a minimum to prevent excessive dilution of alloy weld metal by steel backing.

Because of the normal high penetration of the submerged-arc welding process, it is suggested that alloy weld metal be deposited in two or more layers when it is not possible to compensate for dilution by using a higher alloy welding wire. Procedures resulting in a minimum amount of penetration must be used. All alloy layers except the last pass should be lightly ground or chipped to assist in reducing iron content of the finished weld. As a result of the amount of penetration obtained with automatic welding processes and the small thickness of alloy cladding in relation to the overall thickness of the clad material, the clad side is generally manually welded. (See Chapter 13 for further information on submerged arc welding.)

Preheating for Welding Clad Steels

Preheating lowers the temperature differential between the backing plate metal and the weld metal. It helps prevent cracks in both weld and backing plate metal and reduces shrinkage stresses and distortion. Preheating for welding is not required if the material is of light gage or the weldment of simple design. A preheat of 300 to 400°F. should be used if the backing plate metal is high in tensile strength, if the plates are heavy gage or if the weldment is of rigid design.

Preheating may be required for the welding of all straight-chromium stainless clad steels except Type 405. Type 410 is martensitic and susceptible to small changes in carbon content. It is of a pronounced air-hardening nature unless the carbon content is less than 0.08%. The balance of straight-chromium clads (14–16 Cr, 16–18 Cr) are brittle in the as-welded condition and should be preheated.

These materials should be heated to 300 to 400°F. and held at that temperature range during welding. Preheating may be done locally at the weld zone. After welding has been completed, the structure should be annealed before complete cooling occurs.

Weld Defects

Corrosion-resistant properties required of the clad surface and mechanical properties specified for welds and welded joints demand a high-quality weld. Defects regarded as of little importance in ordinary mild steel fabrication may be of major concern in clad or solid corrosion-resistant materials. Incorrect joint preparation and fit-up result in a tendency to produce many of the common defects. Departure from correct procedures will result in welds of poor mechanical and chemical properties.

Undercutting of the clad surface will reduce fatigue strength and may reduce the thickness or eliminate the protection of the cladding. For example, a 1/4-in. thick, 10% clad plate has 0.025-in. cladding. If this is undercut to any appreciable extent, the corrosion-resistant service life is reduced or lost altogether. All undercut sections should be covered with weld metal.

Inadequate penetration and incomplete fusion of the weld metal will have a tendency to initiate cracks at the unfused area and will also, in extreme cases, coupled with additional defects such as undercuts, offer a channel for corrosive materials.

Porosity occurring in clusters in the weld at the start of a new electrode may be caused by excessive current, instability of the arc, insufficient slag removal, damp electrodes, improper groove preparation, improper electrode manipulation or poor electrode coating. As porosity below the weld surface will act as a stress raiser and porosity on the weld surface will be a focal point for corrosion, this condition should be avoided.

Some electrodes give trouble at the start of a pass due to nonmetallic inclusions found in clusters or groups. This may be overcome by starting the pass on top of the preceding pass and burning off approximately 1 in. of electrode before starting the weld. Excess metal on top

of a pass can be chipped or ground off. Dead shorting the electrode on a copper bar for a brief time prior to welding has proved helpful in some cases.

Stress-Relief Heat Treatment

Some pressure vessels, weldments to be machined, structures with widely different sections, weldments of high hardenability and high-alloy material are examples of materials and structures that should be given a stress-relief treatment. Many codes and specifications require that welded structures of certain materials and proportions be stress relieved after welding.

The range of temperatures used for stress relieving mild steel is 1100 to 1250°F. A temperature of 1200 to 1250°F. produces the greatest amount of carbide precipitation in austenitic stainless steel. Therefore, these materials should not be heated up to a normal stress-relief temperature unless the carbon content is extremely low or the material has been stabilized with titanium or columbium. Type 321 (stabilized with titanium), Type 347 (stabilized with columbium) and Types 316 and 304 with 0.03% C max. can be given a normal stress-relief heat treatment without danger of excessive carbide precipitation. If the structure or service is such that a stress-relief heat treatment is required, one of the stabilized or low-carbon claddings should be used. For some services, precipitated carbides are of no significance and may be disregarded.

Type 410 stainless is martensitic and will harden at slow rates of cooling unless of the low-carbon grade. It may be preheated to 300°F. minimum and given a stress-relief treatment following welding. The same treatment may be used for Type 430. These materials are at times given an annealing heat treatment following welding as noted in Table 2. The annealing treatment, while given primarily to insure high ductility in the weld metal and the heat-affected zone, will act to relieve internal stresses. Type 405 is ferritic and not subject to excessive hardening. However, areas adjacent to the weld may be brittle and the vessel should be heated at 1150 to 1200°F., after welding. (Chapter 43 contains further information on stress relief.)

FINISHING

Many applications require that the weld surface be ground flush or that ripples be removed. Preliminary grinding is generally done with rubber or bakelite bonded aluminum oxide wheels of 16 to 36 grit. The wheel should be free-cutting and generally operates at rim speeds from 5000 to 6000 linear feet per minute. Recommendations of wheel manufacturers should be followed regarding grinding speeds.

Fig. 24.—Process Vessels of 20% Monel-Clad Steel

Edges of the wheel should be rounded and grinding should proceed along the bead, care being taken not to tilt the wheel. A $^{3}/_{16}$-in., 10% clad plate has only 0.01875 in. cladding, and a tilted wheel will soon cut through or seriously reduce the thickness of cladding. The wheel should be allowed to ride the work in the interest of efficiency and should not be held too long in any place because of danger of overheating the clad surface. Heat tinting will appear at approximately 400°F.

Where finer finishes are required than produced with a 36 grit it is customary to use 40 to 60, or finer, grit wheels. If it

is necessary to match a No. 4 plate finish, the weld should not be ground level with the plate or a depression may appear when buffing.

The diameter of the wheel should be small and the wheel should be used only for alloy work.

Buffing and Polishing.—In buffing and polishing of clad steels it is customary to use 18 to 20 sections of unbleached muslin wheels of $^{64}/_{68}$ to $^{84}/_{92}$ count. These wheels are sewed to produce stiffness near the center and flexibility at the edges.

Sandblasting.—No special technique is necessary to sandblast clad plates. Sand should be iron-free and clean. The blast should not be allowed to dwell on any area too long as local erosion and surface irregularities will result. The scales formed on stainless steel are tenacious and may be quite impervious to normal pickling. With these types of scale, care must be taken to protect the cladding from severe local erosion caused by blasting on the unscaled section. Pickling or passivation should follow sandblasting to

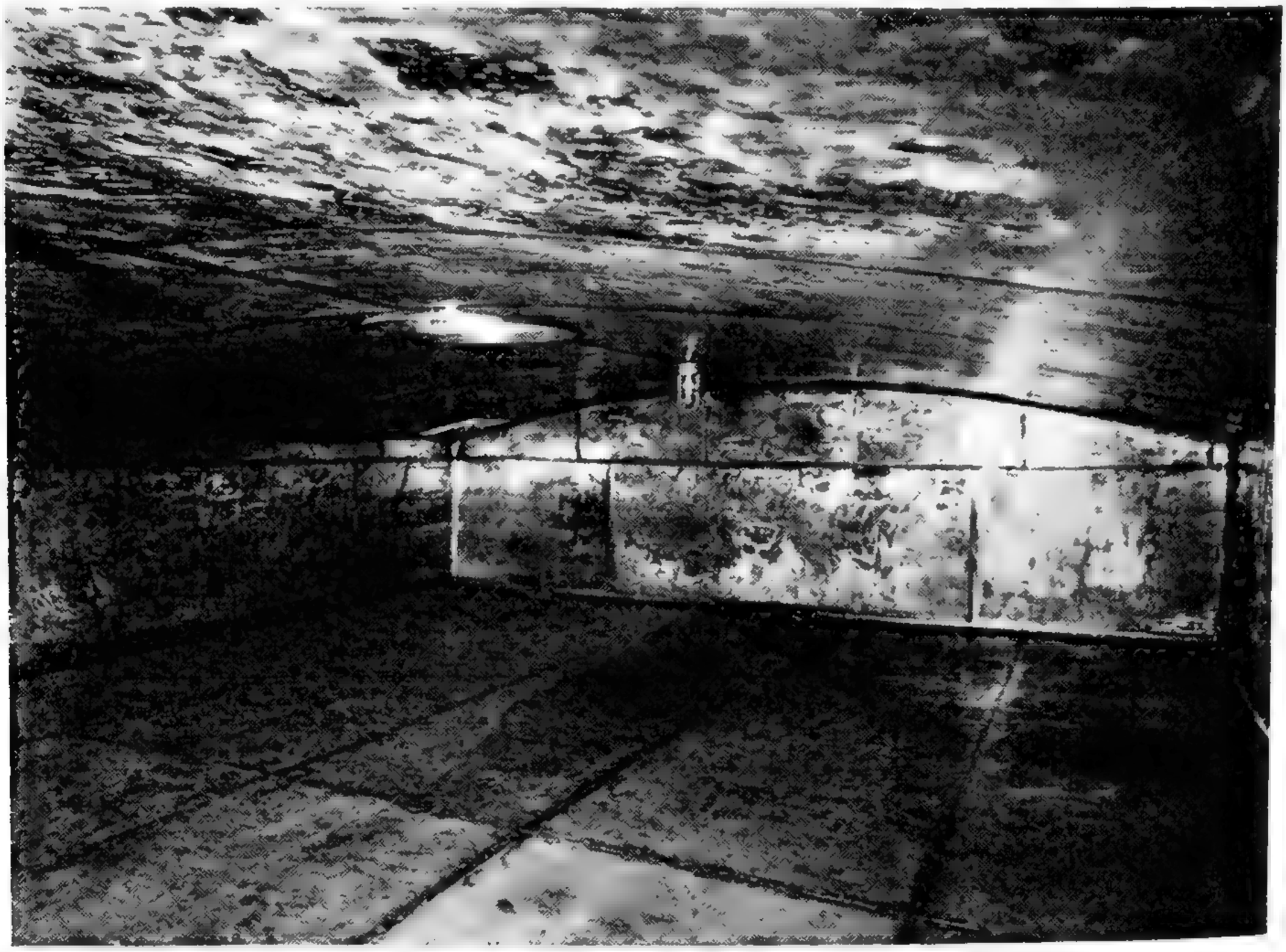


Fig. 25.—Hot Wort Tank of 304 Stainless-Clad Steel

The abrasive used with the wheels is either aluminum oxide or silicon carbide. It is customary to reduce grit size in steps of 40. For example, if 80 grit is used first, it would be followed by 120 and then 160. Or if 100 grit is used in the first operation, it would be followed by 140 and 180 grit. The grit is glued to the wheel, and cardboard or used wheels are inserted between the sections to increase softness and to provide ventilation. It is customary to change direction of the wheel 180 deg. with change in grit size, to help eliminate wheel marks in the plate surface.

insure that all scale and embedded iron are removed.

Pickling, Cleaning and Passivation.—All oil, grease and dirt should be removed by scrubbing with soap, alkali cleaners or suitable solvents to enable the acid solutions to get at or wet the clad surface.

Immersion of clad materials in acid solutions for the time required to remove scale from the clad surface may allow excessive attack of the backing steel. Scale can be removed by short periods of immersion accompanied by swabbing and scrubbing the clad surface with acid solution. Paste pickle incorporating acid

solution with fuller's earth and lampblack may be used on the clad surface; or the steel surface of the plate may be covered with wax or an acid-proof plastic coating.

COMMON APPLICATIONS

Clad steels are used to provide protection from contamination, corrosion resistance and/or heat resistance where they are more economical than for similar protection by solid materials. Clad steels are used in the manufacture of equipment for the petroleum industry, breweries, dairies, bakeries, paper and pulp mills, food processing plants, textile mills and chemical plants.

Code Regulations

Under Case 896 (reopened), published in Mechanical Engineering, December 1948, the ASME Boiler Code Committee approves the use of clad steels meeting the requirements of Boiler Code specification SA-263, SA-264 and SA-265 for the fusion welding of pressure vessels. These specifications correspond to ASTM Specifications A263, A264 and A265. The backing plate may conform to any ASME Boiler Code plate specification approved for welding.

Full thickness (cladding and backing steel) may be used for the design of vessels built of materials complying with the above specifications when corrosion is not expected. When corrosion is expected, additional metal thickness must be provided.

The reader is referred to the text of Case 896 for full details of the special requirements imposed. Typical clad vessels are shown in Figs. 24 and 25.

BIBLIOGRAPHY

1. *Welding Data to Help Fabricator Using Nickel-Clad Steel,* F. P. Huston and T. T. Watson, Welding Engineer, December 1938 and January 1939.

2. *Physical Properties of Iron-Nickel Alloys Formed in Welding of Nickel-Clad Steel,* W. G. Theisinger and F. G. Flocke, The Welding Journal Res. Suppl., March 1939.

3. *Welding and Cutting of Stainless Clad Steel,* W. B. Keelor, The Welding Journal, November 1939.

4. *Pluramelt-Plural Compositions from a New Melting Process,* Vere Browne and H. S. Blumberg, Metal Progress, February 1940.

5. *Armored Steel,* T. W. Lippert, The Iron Age, March 6, 1941.

6. *Methods for the Fabrication of Clad Steel Plate,* Bulletin T-4, International Nickel Co., 1941.

7. *Handling of Ni-Clad Steel,* J. V. Kielb, The Welding Journal, November 1941.

8. *Stainless Steel Arc Welding Techniques,* E. W. P. Smith, Iron Age, April 2, 1942.

9. *Welding Nickel, Monel and Inconel Clad Steels,* W. G. Theisinger, Iron & Steel Engineer, October 1942.

10. *Alloy Steel Cladding and Pressure Vessels,* H. S. Blumberg, Iron & Steel Engineer, October 1942.

11. *Jessop Stainless-Clad Steel,* Jessop Steel Co., 1946.

12. *Clad Steels,* Materials and Methods Manual No. 30, Materials and Methods, September 1947.

13. *Allegheny Ludlum Stainless Plates Solid and Clad and Their Fabrication,* Allegheny Ludlum Steel Corp., 1948.

14. *Fabrication of Lukens Clad Steels,* L. W. Williams, Lukens Steel Co., 1948.

CHAPTER 37B

APPLIED LINERS*

GENERAL PROPERTIES

Definition and General Description

APPLIED LINER construction may be defined in a general manner as a composite plate consisting of a base plate, usually of a commercial grade of mild steel, to one surface of which is attached a relatively thin layer of a corrosion- or heat-resisting metal. Applied liner construction differs from clad construction, described in Chapter 37A, in that the attachment of the relatively thin sheet of corrosion- or heat-resisting metal to the heavier base plate is by an intermittent instead of a continuous bond over the entire surface of the base plate.

Sheet lining may be attached to the base plate by spot or seam welding, by welding through the thickness of the sheet with the submerged arc or by welding plugs into holes cut in the sheet. Strip liners may be attached to the base plate only at their edges by the welding used to join the individual strips to each other.

Applied liners are used to conserve alloying materials and to give a more economical form of construction by the use of a thin veneer of special alloy to combat either corrosion or oxidation at higher temperatures. They are also used when a strong backing material is needed to back up a corrosion-resistant lining which is low in strength.

Two problems are involved in applying the special alloy liners to the base plate. One is the attachment of the liner sheet to the base plate, and the other is the joining together of the individual liner sheets so as to present a continuous surface of the proper alloy for complete protection against corrosion or oxidation.

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* Prepared by a committee consisting of J. J. Chyle, A. O. Smith Corp., *Chairman;* P. C. Arnold, Chicago Bridge & Iron Co.; E. O. Bergman, C. F. Braun & Co.; O. R. Carpenter, The Babcock & Wilcox Co.; James Earthman, Wyatt Metal & Boiler Wks.

Materials and Specifications

Base Plate.—The base or backing plate is generally mild carbon steel, but it may be any weldable low-alloy steel. When used for pressure vessels, the base plate must conform to an approved *Boiler Code* specification and to the design and service requirements of the Code. The base plate should have good weldability and such a composition that the liner can be suitably welded to its surface by the proposed welding process. For pressure vessel construction the following ASTM specifications are commonly used for the base plate:

A-201—Carbon-Silicon Plates of Ordinary Tensile Ranges for Fusion-Welded Boilers and Other Pressure Vessels.

A-203—Nickel-Steel Plates for Boilers and Other Pressure Vessels.

A-204—Molybdenum-Steel Plates for Boilers and Other Pressure Vessels.

A-212—High Tensile Strength Carbon-Silicon Steel Plates for Boilers and Other Pressure Vessels (Plates $4^1/_2$ In. and Under in Thickness).

A-225—Manganese-Vanadium Steel Plates for Boilers and Other Pressure Vessels.

A-285—Low and Intermediate Tensile Strength Carbon-Steel Plates of Flange and Firebox Qualities (Plates 2 In. and Under in Thickness).

The thickness of the base plate depends largely on the type of equipment being fabricated. In general, base plates vary from $^1/_4$ to 5 in. or more in thickness. Applied liners are not economical for base plates less than $^1/_4$-in. thick, and there is relatively little difference in cost between solid alloy plate and applied liner plate in thinner sections.

Liner.—The materials in general use for liners include a wide variety of alloy materials available in sheet or strip form. Most commonly used are the various types of stainless steel, including both

the straight chromium or ferritic types and the chromium-nickel or austenitic types. The straight chromium steels include AISI Types 405, 410 and 430. The austenitic steels are AISI Types 301, 302, 304, 308, 309, 310, 316, 321 and 347. Nickel, copper and a variety of nickel alloys, copper alloys and special corrosion- or heat-resistant alloys are also used.

In the nonferrous field, nickel and nickel alloys are common lining materials. The nickel may be obtained in carbon-free and in other commercial grades. The nickel alloys such as Monel, Inconel and cupro-nickel are quite widely used because of their corrosion resistance to specific chemical conditions. Copper and copper alloys such as the aluminum bronzes and tin bronzes are often used for special chemical corrosion resistance. Some of the special alloys that have been used for specific corrosion resistance are Hastelloy A, B and C; these are composed of chromium, nickel and molybdenum, and have specific corrosion resistance against certain chemical reagents. Some of the more expensive metals such as pure silver, platinum, gold and tantalum are used where extreme resistance to chemicals is necessary.

The dimensions of the liner sheets depend largely on the method of attachment. Widths from 24 to 48 in. are commonly used for sheets attached by resistance welding. The lengths may vary from 3 to 12 feet. The size also depends on the type of alloy used and the sizes in which this material is normally available. The thickness also varies somewhat, depending on the degree of corrosion resistance required and on the type of material used. In general, the thickness varies from $^{1}/_{16}$ to $^{2}/_{16}$ in.; the most commonly used thicknesses are $^{5}/_{64}$ to $^{7}/_{64}$ inch. Liner material thinner than $^{3}/_{16}$ in. is seldom used, except for the very rare metals such as silver, platinum and tantalum. The lighter gages are harder to weld and so are seldom used except when the greater thicknesses are prohibitive in cost.

Filler Metal.—The filler metal used in arc welding the alloy lining should be of such composition that the deposited weld metal will be within the composition range of the lining material. Because of the pickup from the base metal, this may require that the electrode used have a higher alloy content or a lower carbon content, or both, than the lining material. Electrodes of entirely different composition may be used provided they give sound welds with a corrosion resistance equal to or better than that of the liner.

Specifications for filler metal include AWS-ASTM Standard Specifications:

Corrosion-Resisting Chromium and Chromium-Nickel Welding Electrodes (AWS Designation A5.4; ASTM Designation A298).

Copper-Alloy Metal Arc-Welding Electrodes (AWS Designation A5.6; ASTM Designation B225).

Bare electrodes are used only with automatic or semi-automatic submerged-arc or inert-gas metal-arc welding. See Chapters 38 and 61 for further information on welding electrodes.

CODE REQUIREMENTS AND DESIGN

Code Regulations

Rules for the construction of pressure vessels from lined plate are given in ASME *Boiler Code* Case 1078 and in the forthcoming Part UCL of Section VIII of the ASME Code. The rules deal with such subjects as materials, allowable stresses, radiographic inspection, stress relieving and testing. Detailed requirements are given for procedure and operator qualification tests together with tests of the attachment welds of the liner to the base plate. The API-ASME *Code for Unfired Pressure Vessels for Petroleum Liquids and Gases* follows the *Boiler Code* regulations.

Spacing of Attachment Welds

A wide variation is possible in the range of spacing of attachment welds. At one extreme would be the vessel with no attachment welds at all. The nearest approach to this is the layer vessel with an inner layer of corrosion-resistant material in which the circumferential seams and the welding around openings serve as attachment welds. The other extreme is clad plate with 100% attachment. In between are strip, plug, and through-welded, and spot- and seam-welded liners in the order of the spacing commonly used in these constructions.

The important factors determining the spacing of attachment welds are (1) the maintenance at all points of the corrosion-

resistant properties of the lining material; (2) economy of construction; (3) the effect of differences in the thermal expansion rates of liner and base plate.

Possible impairment in corrosion resistance is restricted to the weld zone. Dilution of the weld metal or weld nugget by pickup from the base metal may result in a composition having reduced corrosion properties. In arc welding, the effect of dilution may be overcome by using electrodes of higher alloy content. Where this is not possible, the effect may be minimized by applying the weld metal in two or more layers. In resistance welding, dilution may be kept from the surface of the lining by careful control of the welding operation. The corrosion resistance of many lining materials may also be impaired by cracking in the weld metal or in the heat-affected zone. The incidence of cracking may be reduced by using a wider spacing of attachment welds.

Austenitic steels and many nonferrous alloys have a higher rate of thermal expansion than that of the base plate material. The alloy liner must conform to the expansion of the base plate because of its greater thickness. The liner can do this either by compressing or by buckling or bulging. Compression is promoted by close spacing of attachment welds. It begins as elastic compression, but for any considerable rise in temperature, transforms into plastic flow. Buckling, on the other hand, occurs with wide

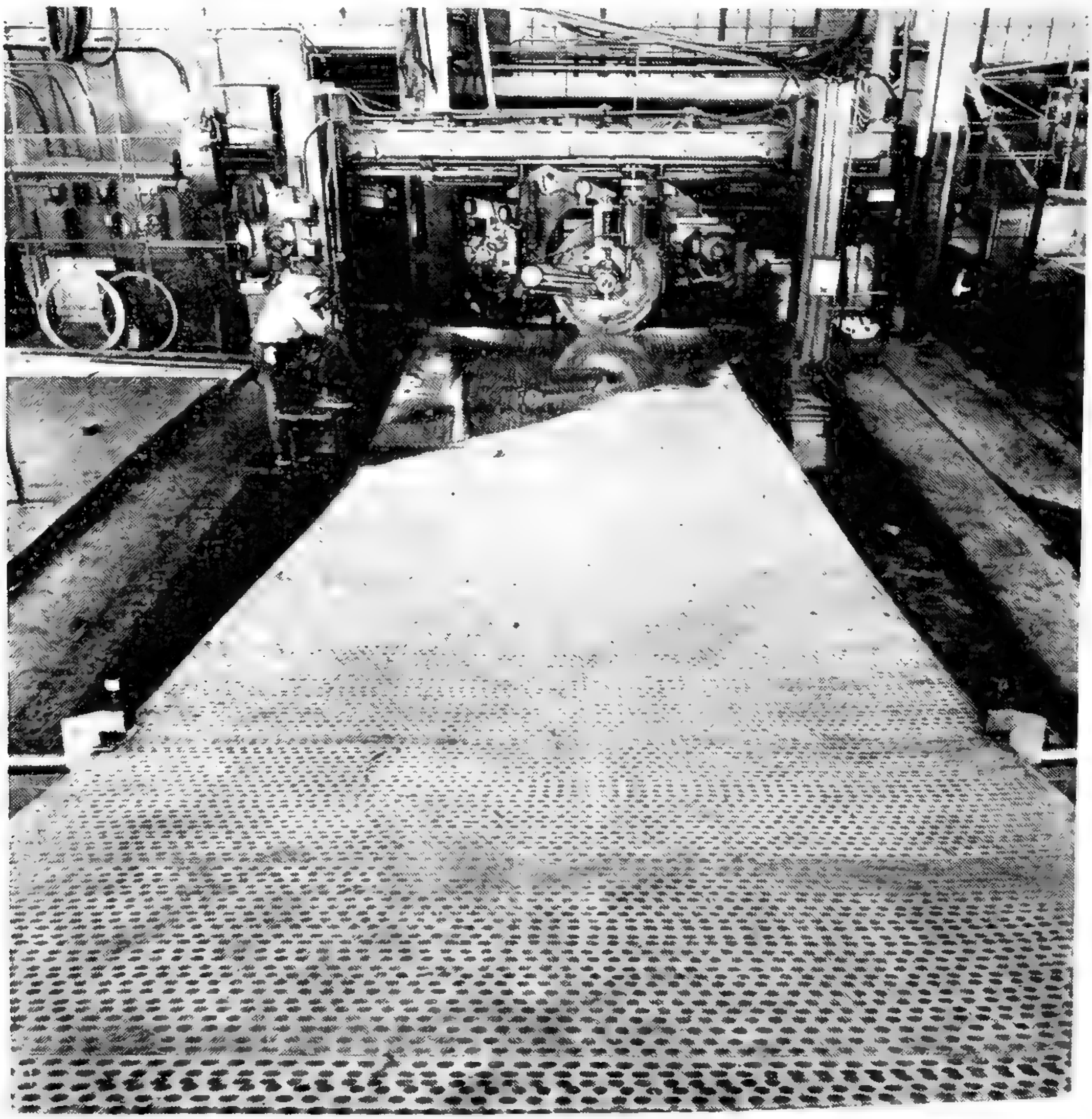

Fig. 1.—Typical Spot-Welding Machine for Liners

attachment spacing. It is elastic at the wider spacings, and at intermediate spacings may be accompanied by plastic flow. The selection of attachment spacing is affected also by the pressure, the operating cycle or service conditions, and the nature of the corroding medium. No general rules for spacing can be laid down. Each case should be given separate consideration.

welding is quite similar to the spot welding method, and uses similar welding equipment. However, the electrodes move continuously without interruption during the welding cycle. A typical seam welding machine is shown in Fig. 2. In seam-welding liners it is common to use a plurality of alloy liner sheets, as shown in Fig. 3, in order to obtain the proper bonding of the liner to the base plate. The corrosion-resisting liner may be composed of two thicknesses of liner sheets which are placed over a relatively thin sheet of nickel directly over the base plate. The purpose of the two sheets of alloy liner is to provide flexibility while the nickel sheet is used to prevent excess dilution of the base metal from the welds. The use of more than one thickness of alloy liner is not limited to seam welding, but can also be used in spot welding previously described.

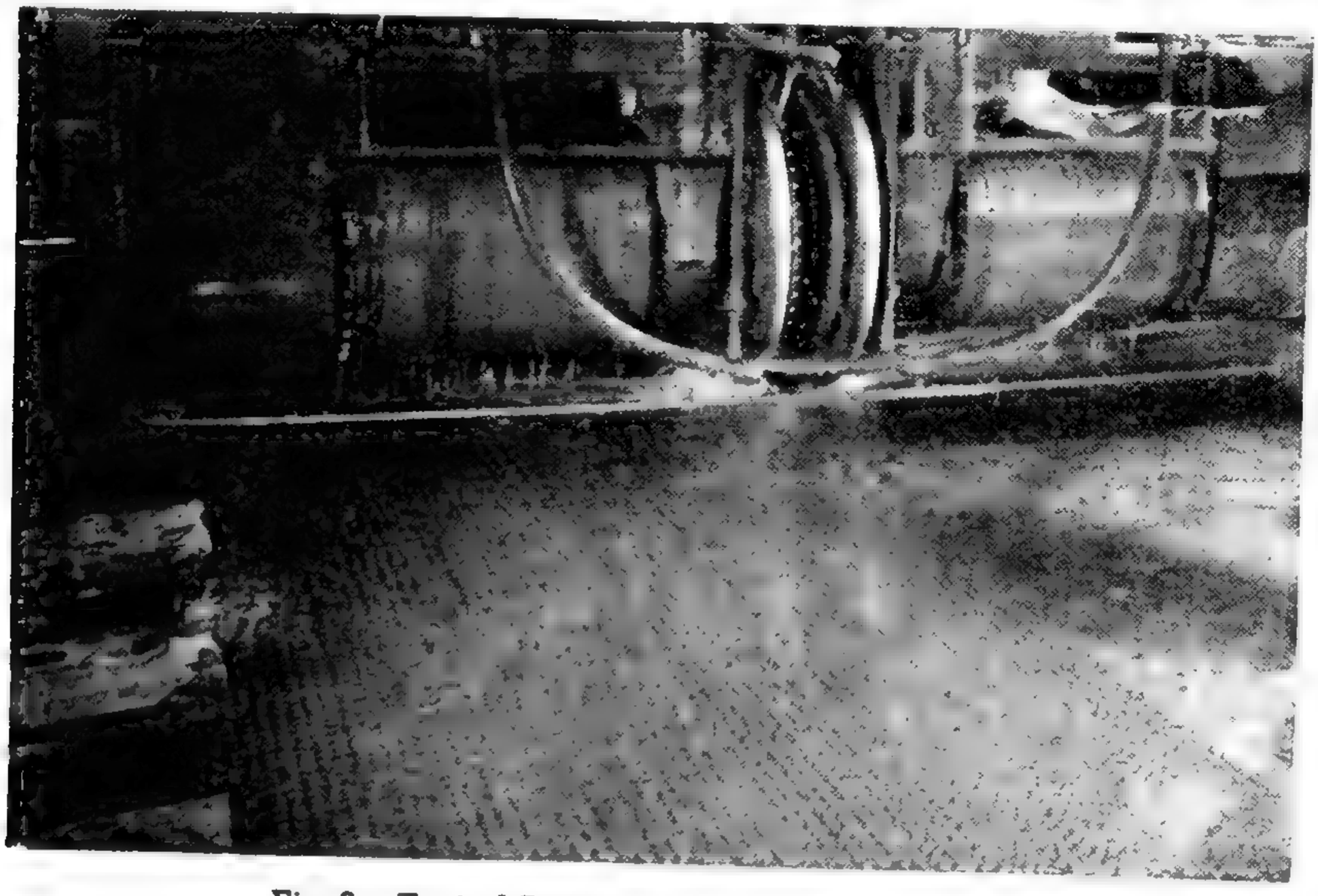

Fig. 2.—Typical Seam-Welding Machine for Liners

FABRICATION

Equipment

Special resistance welding equipment is usually designed for spot or seam welding liners. A typical spot-welding machine is shown in Fig. 1. This machine consists primarily of two circular electrodes, spaced from 3 to 12 in. apart, that move over the surface of the liner plate. Two spot welds in series are made simultaneously with this type of machine. The current enters the liner material through one electrode and emerges from the other. The electrode wheels move intermittently, being held stationary at the time the weld is made. The transformer is made an integral part of the rotating electrodes in order to reduce the length of the secondary unit from the transformer.

The attachment of liner sheets by seam

Through welding is usually done with automatic submerged arc welding equipment. A typical setup is shown in Fig. 4. The desired penetration is obtained by varying the voltage, current and speed of travel. Similar equipment may be used for making the weld joints between adjacent sheets of spot or seam-welded liners or between the strips of strip lining.

Surface Preparation

Special preparation of the liner and the base plate is required for both resistance and arc welding. The base plate must be clean and free from surface contaminations such as scale, grease, oil and paint, and its surface should be reasonably smooth and free from gouges, low spots and pockmarked surfaces. It is customary to sandblast the surface of the carbon steel plate prior to attaching the liner.

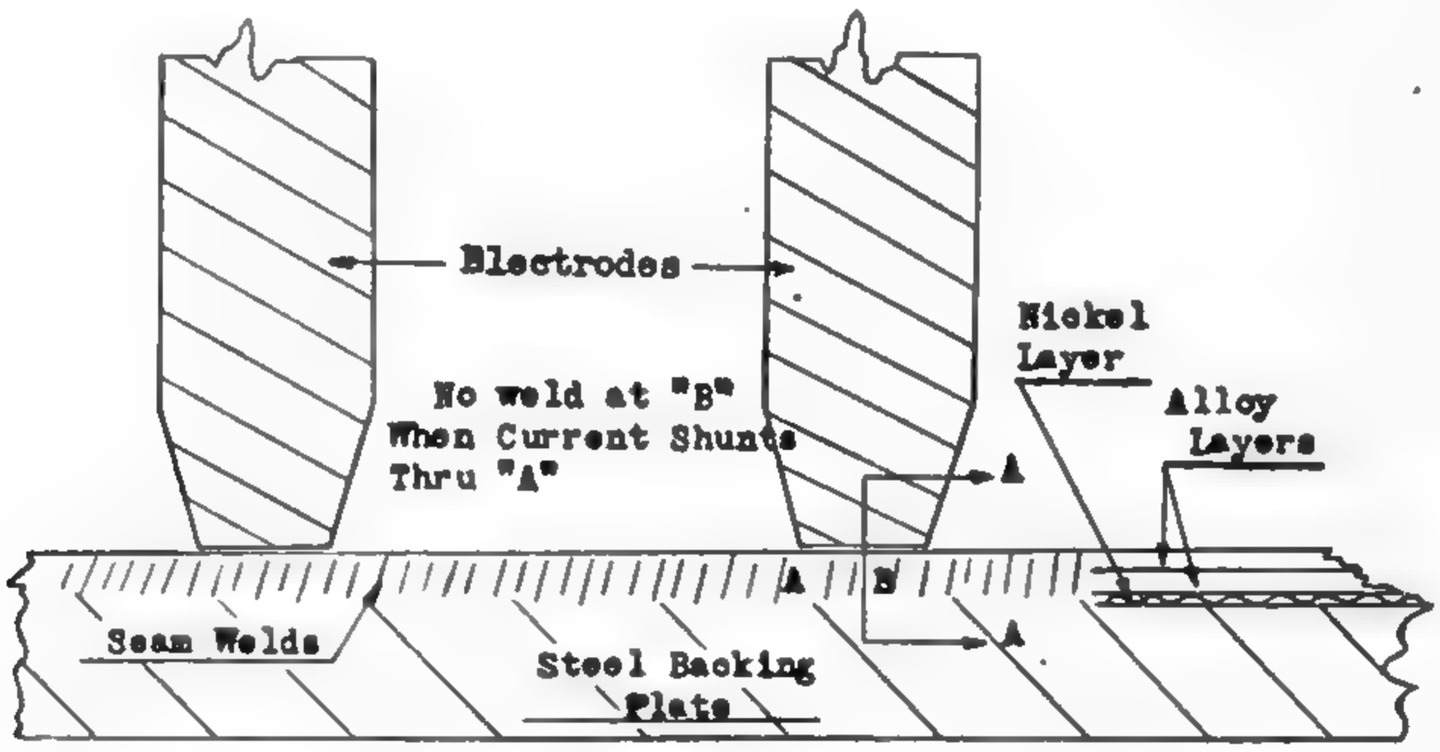

Fig. 3.—Seam Welding with Multiple Alloy Liner Sheets

The liner material is usually purchased with a pickled cold-rolled finish, sometimes referred to as a *standard 2D finish* for stainless alloys. It is important to have the surface clean and free from such defects as pits, rust and foreign material imbedded in the surface, and with the proper finish for corrosion resistance. The surface finish of the liner sheet and the surface preparation of the base plate are of prime importance for resistance welding, and both are purchased with special requirements as to their finishes. For many applications where corrosion is a major factor, the liner material is specified with a certain guaranteed corrosion resistance which is agreed to by the purchaser and the supplier. In many cases the liner material is given a heat treatment to meet the corrosion requirements of the particular alloy. The effect of welding heat on the corrosion resistance of such materials must be considered.

Joining Adjacent Liners

Adjacent sheets or strips may be welded together either by manual or automatic metal-arc welding processes, including automatic submerged arc welding. The usual construction is to have the weld at the joint penetrate into the base plate so that it serves as an attachment of the liner to the plate. This assures complete penetration of the liner and makes it possible to pressure test behind each separate liner panel. The strip method of lining uses no attachment other than the joint weld. The edge preparation and the root opening depend on the liner composition and thickness and on the welding process. Liners up to $^1/_{16}$-in. thick need no edge preparation for manual welding; the thickness may be considerably greater when submerged arc welding is used. A simple type of edge preparation consists in beveling the edges of the abutting liners with a chipping tool. The root opening between the liners may vary from zero up to $^1/_2$ in. or more. Wider root openings are usually employed with strip linings. Several types of such joints are shown in Fig. 5.

Attachment of Liners

Four methods of attaching the liner to the base plate are commonly employed. Strip lining uses narrow strips without interior attachment, the attachment being by means of the joint welds discussed in the preceding section. Spot and seam welding, through welding and plug welding are used with larger liner panels that require other attachments in addition to the edge welds.

Strip Lining.—In strip lining, the attachment of the liner to the base plate is by means of the welds that join adjacent sheets. The lining is in the form of strips of such width that no attachments are required in the interior of the panel.

The strip lining method has a wide

range of application. Almost any metal which is available in sheet form and is capable of being welded can be applied as a lining by the strip method. One exception is hot-short material that cracks during cooling, due to the restraint offered by the thicker base plate.

The length of the strips may vary from 24 to 40 in. for field-applied liners, or from 24 to 120 in. for shop-applied liners, depending on the type of equipment and the construction. The width of the strips depends largely on operating temperatures, and may vary from 3 to 6 in.; the narrower widths being used for the higher operating temperatures.

used with strip linings. Another procedure commonly used is shown in Fig. 5 (*b*). The edge of each of the adjacent strips is welded with a fillet weld. Then the space between the two welds is filled with a cover weld. The use of a cover weld reduces the danger of weld dilution from the base metal. Special weld joints that prevent any weld dilution are shown in Figs. 5(*a*) and (*c*). A strip-lined vessel is shown in Fig. 6.

Spot and Seam Welding.—The equipment used has previously been described and is covered in more detail in Chapter 15. The spacings between spot welds may vary over wide ranges from 1 × 1 to 3 × 3

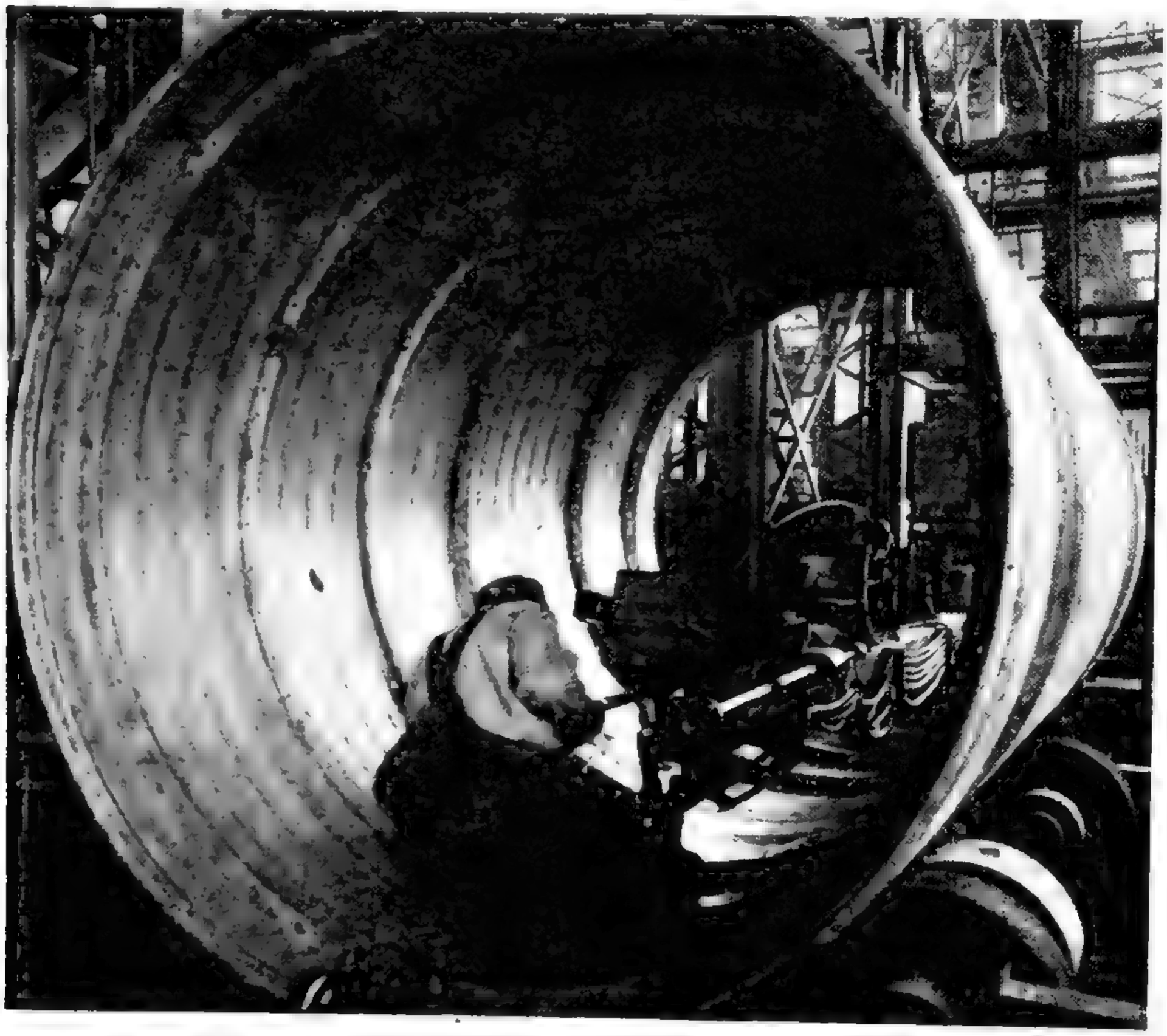

Fig. 4.—Typical Submerged-Arc Welding Equipment for Liners

Strip linings may be applied to vessels that have been in service, as well as to new vessels. Field attachment is performed manually and may require welding to be done in the flat, horizontal, vertical and overhead positions.

The weld procedures described in the preceding section for joint welds may be

inches. Spacings such as 1 × 1½ in. or 1½ × 1½ in. or other combinations are possible, the desired spacing usually being determined by the service conditions. Closer spacings are recommended for high temperatures and rapid cooling and heating cycles. Where changes in temperature do not occur, wider spacings are used.

A typical oil refinery vessel which has a spot-welded liner with adjacent liners attached by manual metal-arc welding is shown in Fig. 7. The spacing between seam welds is kept to a minimum so that the welds overlap to a considerable extent. For seam welding it is customary to use multiple-ply liner sheets to obtain greater flexibility. In some cases a nickel sheet 0.010-in. thick is used against the carbon steel plate. The rest of the liner may consist of several plies of alloy material each approximately 0.054-in. thick. The thicknesses of liner and a nickel sheet make a total thickness of approximately 0.115 inch.

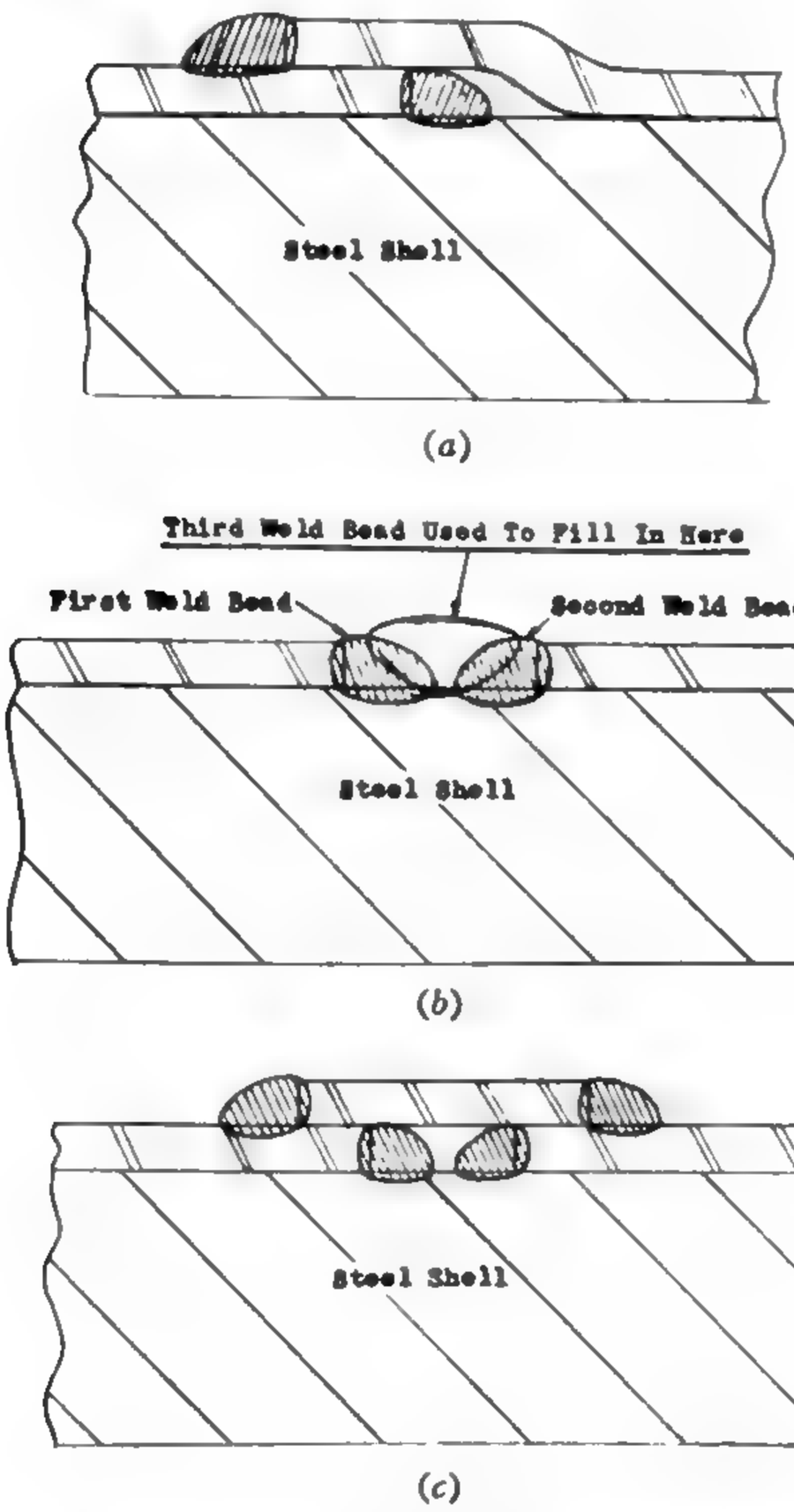

Fig. 5.—Typical Joints for Connecting Adjacent Liners

Spot and seam welding are limited entirely by the composition, thickness and resistance of the liner material, and by the spacing between the welds. Spot and seam welding are somewhat restricted to alloys of higher electrical resistance because the series welding circuit which is used results in shunting of the welding current to such an extent that bonding is difficult. The various types of ferritic and austenitic stainless alloys and the nonferrous metals such as nickel, Monel, Inconel and Hastelloy are commonly resistance welded to the base plate.

Through Welding.—Through welding consists in attaching the liner panel by depositing a weld along the edge of each panel and also a series of welds across the liner, fusing through the liner material and penetrating into the base plate. The depth of penetration may vary, but the usual depth is $^{1}/_{16}$ inch. The attachment welds are generally made with the submerged arc process, and are made either on flat plates or after the plates have been fabricated into cylinders. The welds are made around the circumference of the vessel.

The size of liner sheet is not restricted by the welding equipment. A sheet width of 36 in. is commonly used. The length is selected to provide one, two or three courses around the vessel, depending on its diameter. Joints made in the base plate after the plate is lined may be covered with closing strips attached as described in the section on Strip Lining.

Plug Welding.—Plug welding is a method of attaching a lining by welding it to the base plate through holes punched or drilled through the liner. The holes, which vary in size according to the thickness of the liner, are filled with weld metal which bonds to the base plate and to the liner around the edges of the hole. The edges are usually chamfered in liners over $^{1}/_{8}$-in. thick. If the hole is made too small, difficulty may be experienced in welding and excessive porosity and imperfect bonding to the base plate may result.

Figure 8 shows a typical plug weld construction.

Manual arc welding is largely used for plug welding. Semi-automatic welding using inert-gas or granular-type shielding can be used with some lining materials. Plug welding has been largely replaced by other methods of lining because of the difficulty of making plug welds that are sound and tight in many types of liner material.

Welding Details

Suitable corrosion-resisting metal must be used to cover the carbon steel weld metal in the main longitudinal and girth seams, as well as in the welds of

miscellaneous internal details, such as nozzles, manways and openings. In some cases deposit welds are made over the main seam welds. In others, the cover strip method of protection is used as shown in Fig. 5 (*c*). The type of construction used to protect the main seam welds depends to a large extent on the type of alloy used, the code requirements and the specification to which the vessel is built.

Fig. 6.—Strip Lined Vessel

When radiographic or magnetic particle inspection is necessary, such inspection is sometimes performed before the main seam is given the final corrosion protection weld, and sometimes after the corrosion resisting weld metal is applied.

The ASME *Boiler Code* requirements serve as a guide.

Heat Treatment

It is important to heat treat some liner materials to obtain the maximum corrosion resistance. The electrical conductivity may also depend on heat treatment and for this reason special requirements may be necessary for material that is to be resistance welded.

Proper heat treatments for corrosion requirements are usually determined for each type of alloy and are specified for the liner material. Some alloys require stress-relief heat treatment to remove the residual welding stresses set up by the welding operation. Stress relief may also temper or reduce the hardness of the heat-affected zone in the base plate adjacent to the welds, as well as reduce the hardness of the weld in the liner material itself. Some requirements for heat treatment are given in the ASME *Boiler Code*.

Field Welding

The attachment of lining to assembled field vessels by strip lining can be accomplished by using procedures as outlined previously in this chapter with a few exceptions. Because of the difficulty of handling liner strips on scaffolding and in precarious positions while the vessels are in the vertical position, it is suggested

that all liner sheets be as small as possible, preferably not over 40 in. long. This short length will also enable one or two men to apply the liner so that it can be in full contact with the base plate. It is extremely important that the liner be pressed against the shell by some mechanical means to insure full contact. In some cases for smaller diameters, it is necessary to roll the liner plates in the shop to the proper curvature before applying in the field. If possible, on field erected vessels, all oxidation and scale should be removed from the base material either by wire brushing or sandblasting. Sandblasting is, of course, the most satisfactory method as it will detect any corrosion pits or defects in the base plate. In order to minimize the amount of field welding, the joints between the strips should be kept to a minimum. However, they should still be far enough apart so that the two strips can be attached to the base material and then covered over with the final bead. The method of testing liners applied in the field should be a matter of agreement between the purchaser and the fabricator.

TESTING

Procedure and Welder Qualifications

The ASME *Boiler Code* specifies requirements for qualification tests of the welding procedure and of the welders making the joint welds between liners. The *Boiler Code* also gives requirements for the attachment welds between the liner and the base plate.

Testing for Leaks

The method used for testing the tightness of applied liners depends on the type of liner material, the method of construction and the service in which the vessel is to be used. Test procedures include application of fluid pressure on one side or the other of the liner, as well as examination in the vicinity of welds by radiographic, magnetic particle or penetrating oil methods.

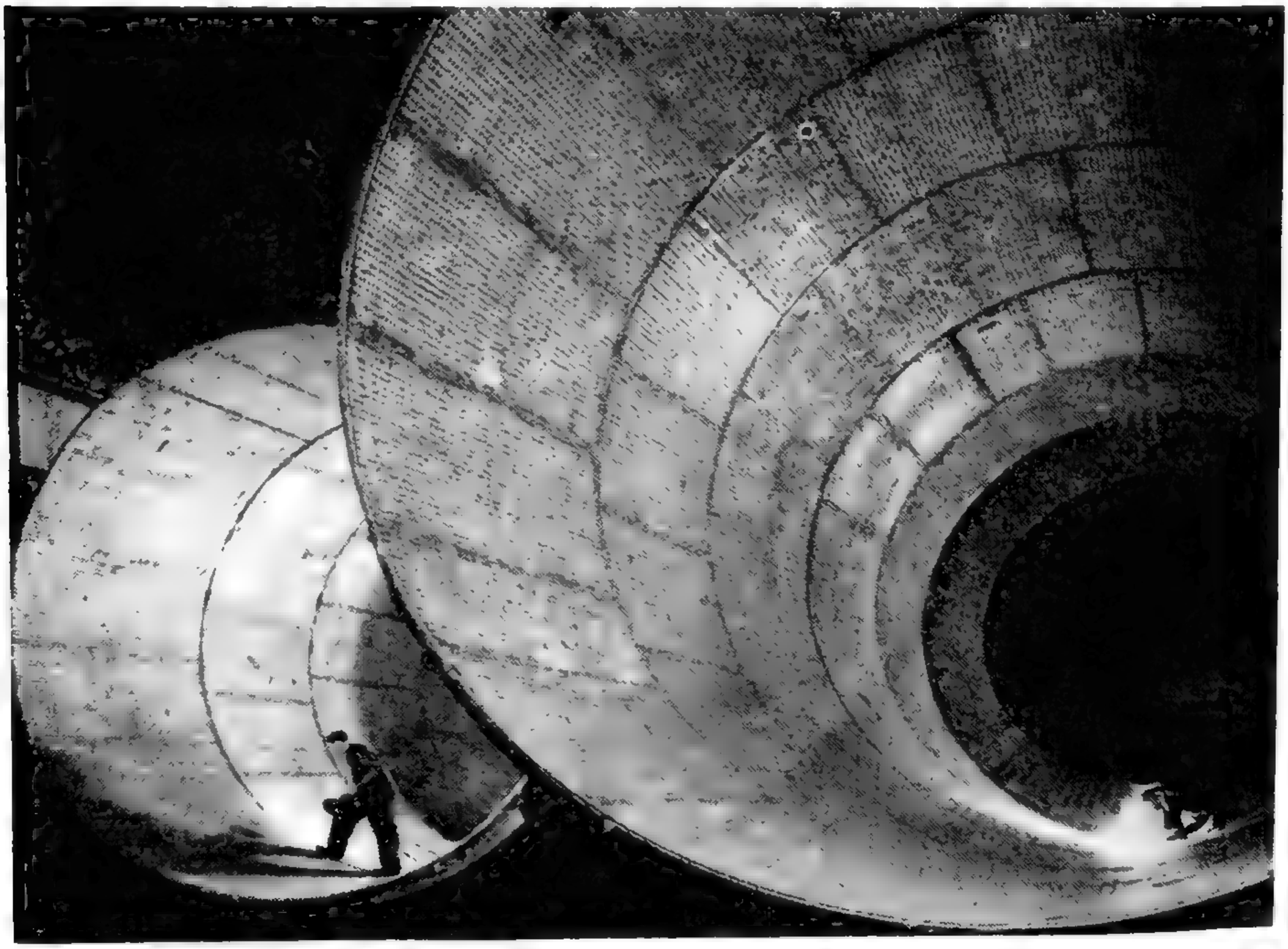

Fig. 7.—Vessels with Spot-Welded Liners

Pressure Testing.—A pressure test behind the liner, using air, nitrogen or some other fluid, is easy to make and is widely used. The pressure is applied

through a hole drilled in the liner or the base plate. If the hole is in the liner, other test methods must be used on the weld that closes up the hole. A soap solution is commonly used to detect air leaking through the liner or the welds. The test pressure should be low enough so that the air will bubble through the soap solution rather than blow it away.

The hydrostatic test required by the leaks are located with an air and soap solution test applied from the reverse side.

The pressure test appears to be simple to apply, and reasonably certain to detect any leaks that may be present. In practice it may fall short of this. The difficulty comes from the application of pressure behind the liner. This reverse pressure alters the configuration of the liner and may close up leaks under test

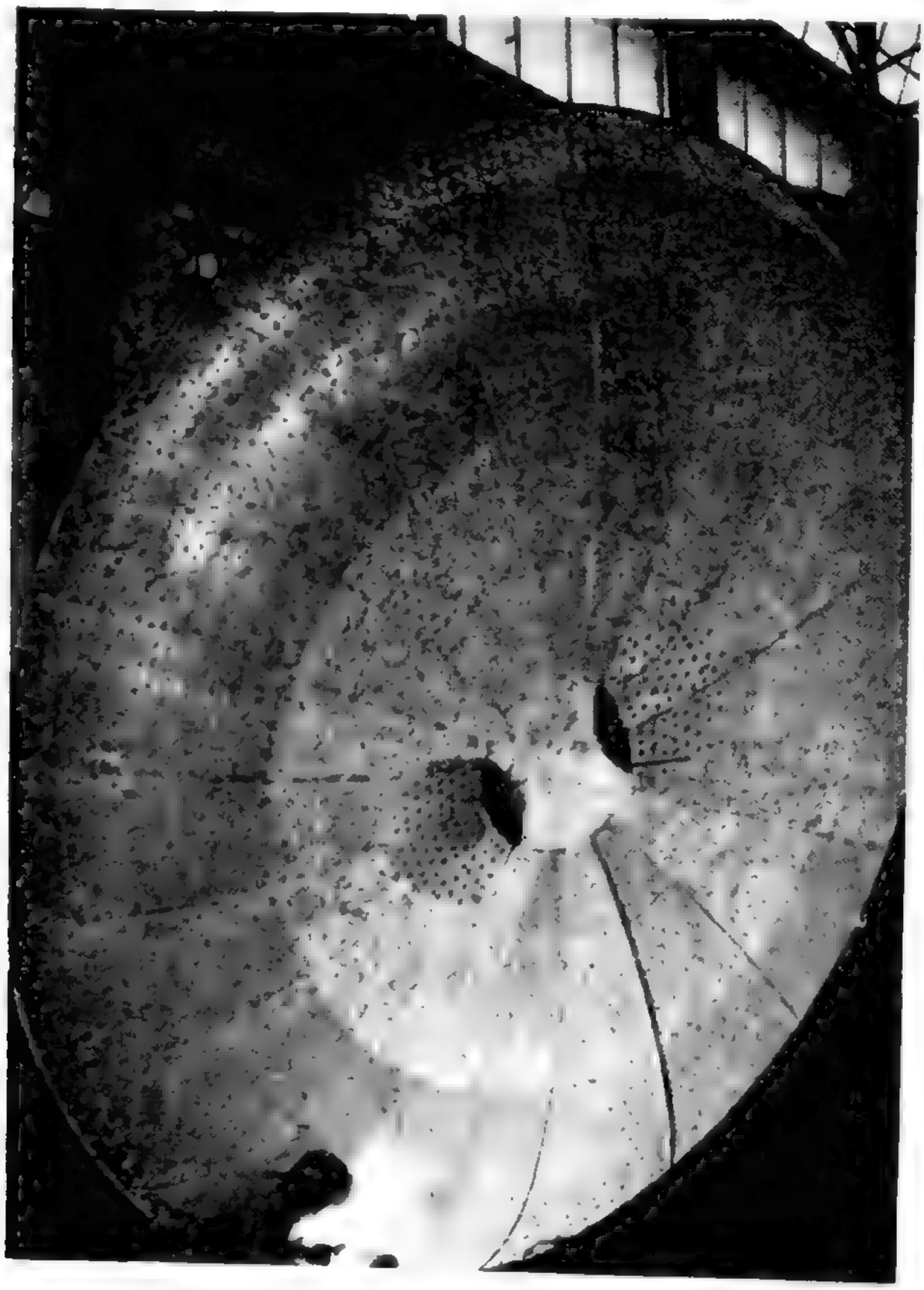

Fig. 8.—Vessel with Plug-Welded Liners

Boiler Code is sometimes used as a test of the liner. One method is to test with oil and then steam out the vessel. Back seepage or bleeding of oil from behind the liner shows up visibly. Another method that has been tried is to provide weep holes through the shell behind each panel, and test with water. If water shows up at the weep holes during the hydrostatic test, the that show up under operating conditions. For the same reason it fails to locate leaks that show up under the hydrostatic test.

Care should be taken that all moisture is removed from behind the lining before the test plugs are closed after the hydrostatic test. This can be accomplished by heating the lining with a torch, or in the case of small or medium

size pressure vessels, inserting in a stress-relieving furnace and raising to a temperature higher than 212°F.

Other Inspection Methods.—Leakage of the liner will occur principally in the welds and heat-affected zones. Several inspection methods are used for locating such leaks. One method uses fluorescent penetrating oil and black light. Another uses a colored penetrating oil. A magnetic particle method may be used on magnetic materials. Radiography is specified for certain liner materials by the ASME *Boiler Code* and may be used for others.

COMMON APPLICATIONS

One of the most important fields of application for applied liners is in the oil industry, in which corrosion protection of the carbon steel plate is of utmost importance. The most commonly used liners in this industry are straight chromium stainless steel Types 405 and 410. A considerable amount of austenitic Types 302, 304, 308 and 309 is also used. Monel, nickel and Inconel are also used extensively in certain types of vessels in the oil industry. Typical vessels for use in the oil industry are shown in Fig. 7.

Because of the corrosive conditions in the paper industry, alloy lined vessels are now commonly employed in the digestors for making paper pulp. The alloys used usually depend on the process. The most commonly used are the austenitic stainless Types 347 and 317. Inconel and Monel are also finding use in this industry.

In the chemical industry applied liner vessel construction is widely employed. The type of lining may vary considerably depending on the corrosive conditions encountered. The chemical industry probably has the widest need for corrosion protection, and as a result there are widely different alloys used. These include all of the stainless steel types of alloys and also the nonferrous alloys, including the nickel, copper, molybdenum and silver linings.

BIBLIOGRAPHY

1. *Field Installation of Chromium Sheet Linings in Pressure Vessels,* J. I Shaler, Refiner and Natural Gasoline Manufacturer, May 1939.

2. *U.S.S. Stainless and Heat Resisting Steels for the Petroleum Industry,* Carnegie-Illinois Steel Corp., 1940.

3. *Field Lining of Refinery Vessels with Stainless Steel Sheets or Strips,* K. E. Luger, Refiner and Natural Gasoline Manufacturer, February 1940.

4. *Surface Cladding,* G. E. Guder, Jr., Steel, August 26, 1940.

5. *Layout and Application of Stainless Strip Lining to Refinery Vessels,* W. W. McClow, Refiner and Natural Gasoline Manufacturer, December 1940.

6. *Adapting Old Equipment to New Uses,* D. E. Evans and W. S. Meyer, Petroleum Refiner, November 1944.

7. *Welding Corrosion-Resistant Alloys to Protect Process Equipment and Technique of Lining Pressure Vessels,* J. A. Gallagher, Petroleum Refiner, April 1945.

8. *Procedure for Application of Stainless Steel Strip Liners to Refinery Vessels in the Field,* K. E. Luger, Petroleum Refiner, May 1945.

9. *The Role of Straight Chromium Stainless Steels for Refinery Vessel Linings,* W. J. Jackel, Corrosion, June 1945.

10. *Pressure Vessels Made with Welded Nickel Alloy Liners,* T. H. Menaugh, Materials and Methods, May 1946.

11. *The Manufacture and Application of Composite Plates,* O. R. Carpenter, The Welding Journal, April 1948.

12. *Cases 897 and 1078,* ASME Boiler Code, American Society for Mechanical Engineers. 1947.

CHAPTER 38

FILLER METAL*

INTRODUCTION

NEW APPLICATIONS of welding in recent years have been greatly facilitated by the development of many new and improved types of electrodes and welding rods, each designed to do specific jobs with maximum efficiency. To provide the users of these materials with a means of evaluating the filler metal available for their use the AMERICAN WELDING SOCIETY and the American Society for Testing Materials, through the jointly sponsored Committee on Filler Metal, have prepared or are preparing specifications to cover the following materials:

1. Mild Steel and Low-Alloy Steel Electrodes
2. Iron and Steel Gas-Welding Rods
3. Aluminum and Aluminum-Alloy Filler Metal
4. Corrosion-Resisting Chromium and Chromium-Nickel Filler Metal
5. Nickel and High-Nickel-Alloy Filler Metal
6. Copper and Copper-Alloy Filler Metal
7. Brazing Filler Metal
8. Surfacing Filler Metal

Current Specifications, at the time of publication of this edition of the HANDBOOK, are reproduced in Chapter 61, and are the Specifications referred to throughout this chapter.

The purpose of this chapter is not to reproduce the Specifications, but to provide a general coverage of the characteristics of the most important commercially available classifications of filler metal in the above categories.

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* Prepared by a committee consisting of J. H. Deppeler, Consulting Engineer, *Chairman*; J. L. Christie, Handy and Harman; O. B. J. Fraser, The International Nickel Co.; G. O. Hoglund, Aluminum Company of America; G. M. Leigh, Metal & Thermit Corp.; David Swan, Union Carbide and Carbon Res. Labs.; C. E. Swift, American Brass Co.; R. David Thomas, Jr., Arcos Corp.

MILD STEEL AND LOW-ALLOY STEEL ELECTRODES

General

Two separate specifications, *Mild Steel Arc-Welding Electrodes* (AWS Designation A5.1; ASTM Designation A233) and *Low-Alloy Steel Arc-Welding Electrodes* (AWS Designation A5.5; ASTM Designation A316) have been issued to cover these electrodes. The former specifications cover electrodes of the E60 series of classifications, the latter electrodes of the E70, E80, E90 and E100 series of classifications. They are discussed together here only as a matter of convenience since from the standpoint of operating and usability characteristics, electrodes of similar classifications in the different series (E6010, E7010, E8010, etc.) are quite the same. Differences will be pointed out as necessary.

The electrodes described in the specifications may be grouped according to (*a*) operating characteristics, (*b*) type of covering and (*c*) characteristics of deposited metal. Operating characteristics and types of covering are described in some detail in the Specifications. Characteristics of deposited metal are described only to the extent of mechanical properties. No requirements have been established for chemical composition or thermal characteristics.

Electrodes, regardless of trade name, which meet all of the requirements of any given AWS-ASTM classification, may be expected to have major characteristics which are very similar if not identical. Certain minor differences continue to exist among brands due to differences in production facilities and the usual differences of opinion that exist in any field regarding specific operating characteristics. The more important characteristics of each electrode classification are discussed later.

With regard to the low-alloy steel electrodes it should be noted that electrodes of the same classification may deposit metal of different composition and different thermal characteristics. In weldments where mechanical properties either in the as-welded or stress-relieved condition are the only requirements, other characteristics are of little importance; however, in weldments to be heat treated, consideration should be given to depositing metal having thermal characteristics comparable to those of the base metal. Some alloy steels have compositions that give special properties such as corrosion resistance. When welding these steels, an attempt should be made to obtain deposited weld metal having similar properties. Naturally, depositing weld metal having the same composition as the base metal would give such special requirements; however, some alloying elements in the steel cannot be effectively transferred across the arc. It then becomes necessary to substitute another element that can be satisfactorily deposited.

Because of the great variety of compositions available, it is impossible to recommend applications for the low-alloy steel electrodes where properties other than mechanical properties are required. The characteristics of various alloy steels are generally known and from this information it is possible to predict the characteristics of the weld metal of a given composition. For the most part, it will be found that alloys containing molybdenum will have increased creep-resisting properties at elevated temperatures. For this reason, molybdenum alloys are frequently used for fabricating high-temperature, high-pressure power installations. Power installations operating at the higher temperature ranges are frequently fabricated with electrodes depositing a chromium-molybdenum alloy. The chromium unites with the carbon to reduce graphitization in the heat-affected zone.

Most weldments made using low-alloy electrodes are stress-relieved before being placed in service. For this reason, the Specifications define mechanical properties of the weld metal in the stress-relieved condition. It should be kept in mind that with the exception of the deposits of EXX15 and EXX16 electrodes, the as-welded deposits will have a higher tensile strength and yield point and a lower elongation and reduction of area than when stress-relieved. It is not necessary that all weldments be stress-relieved to give satisfactory service. However, if maximum ductility and impact properties are to be obtained from deposits made using an electrode with a conventional type covering, then the weldment should be stress-relieved. The tensile strength and ductility requirements given in the Specifications are considered to adequately describe the stress-relieved deposits of electrodes covered by the Specifications and further elaboration is unnecessary.

EXX10

EXX10 electrodes are designed to produce the best possible mechanical properties consistent with good usability characteristics in all welding positions, using d.c., reversed polarity only. They are characterized by a deeply penetrating, forceful, spray-type arc and a readily removable, thin, friable slag which may not seem to completely cover the deposit. Fillet welds are usually relatively flat in profile and have rather coarse, unevenly spaced ripple. The covering is high in cellulose, usually exceeding 30% by weight. The other materials generally used in the covering include titanium dioxide, various types of magnesium or aluminum silicates, metallic deoxidizers such as ferromanganese and liquid sodium silicate. The core wire is usually a rimmed steel containing 0.10 to 0.14% carbon, 0.40 to 0.60% manganese, 0.04% max. sulfur and phosphorus and 0.025% max. silicon.

Electrodes of these classifications (or EXX11) are recommended for all-position work where the quality of the deposit is of greatest importance, particularly on multiple-pass applications in the vertical and overhead positions, where radiographic requirements must be met.

The majority of applications for E6010 electrodes are on mild steel. However, this classification has been used to advantage on galvanized plate and on some low-alloy steels. Typical applications include shipbuilding, structures such as buildings and bridges, storage tanks, piping and pressure-vessel fittings. Since applications are so widespread, a discussion of each is impractical. In some cases the $^{3}/_{16}$-in. diam. is available in two covering thicknesses, either of which can be used in all positions. Improved mechanical properties are obtained with the heavier covering at some sacrifice of

operating characteristics in the vertical and overhead positions. By far the larger volume is produced with the thinner covering. Sizes larger than $^{3}/_{16}$ in. are, of course, not generally used in all positions.

Generally speaking, the maximum currents that can be used with all EXX10 electrodes are somewhat limited as compared to the EXX12, EXX15, EXX20 or EXX30 electrodes due to the high spatter loss and decomposition of covering that occurs with high currents. Table 1 gives current and voltage ranges which may not apply to every brand produced, but will be found to be satisfactory for most.

The mechanical properties of E6010 to be expected in the as-welded condition, when deposited in accordance with the test procedures prescribed in the Specifications, are shown in Table 2. Since E6010 electrodes contain no alloy ingredients other than those usually contained in the core wire, the chemical composition of the deposited metal, uncontaminated by plate material, will usually show less carbon and manganese than the core wire. The phosphorus and sulfur will not exceed 0.04% each. The silicon content, however, will be higher than that of the core wire and in the case of some brands may approach 0.30%.

No corresponding values are given for the low-alloy steel electrodes because their properties will vary according to their composition, heat treatment, etc.

EXX11

EXX11 electrodes are designed to duplicate the usability characteristics and mechanical properties of the EXX10 electrodes using alternating current. Although also usable with d.c., reverse polarity, a sacrifice in usability characteristics will be noted when compared to the EXX10 electrodes. Penetration, arc action, slag and fillet-weld appearance are very similar to those expected from EXX10 electrodes.

The coverings are also high in cellulose and are classified as the *high-cellulose potassium type*. In addition to the other ingredients usually found in EXX10 electrode coverings, small quantities of calcium and potassium are usually present. The core wire used, so far as is known, is identical to that used in EXX10 electrodes. The necessary alloys for the low-alloy steel electrodes are usually added to the deposit through the covering. Like the EXX10 electrodes, EXX11 electrodes perform satisfactorily on galvanized plate.

The current and voltage ranges for these electrodes are the same as those recommended for the EXX10 electrodes as shown in Table 1.

The mechanical properties of deposited metal obtained from E6011 electrodes are shown in Table 2. The chemical composition of the deposited metal will fall within the same ranges given for E6010 electrodes.

E6012

E6012 electrodes have no corresponding counterparts in the low-alloy steel electrode series of classifications. They are usable in all positions with d.c., straight polarity and a.c., and are characterized by medium penetration, a rather quiet arc, slight spatter and dense slag completely covering the deposit. The covering is high in titania, usually exceeding 35% by weight, which accounts for its being referred to as the *titania* or *rutile type*. In addition, the covering usually contains various silicious materials such as feldspar and clay, small amounts of cellulose, ferromanganese and sodium silicate as a binder. Also, small amounts of calcium compounds may be used to produce satisfactory arc characteristics with d.c., straight polarity. The core wire is identical with that used for E6010 and E6011 electrodes. Whereas single-pass welds may meet with radiographic requirements, multiple-pass welds fall far short.

Generally speaking, fillet welds tend to be convex in profile, having a smooth, even ripple in the horizontal position and a widely spaced ripple in the vertical position, which becomes smoother and more uniform as the size of the weld is increased. Ordinarily, a larger size fillet must be made in the vertical and overhead positions than with E6010 and E6011 electrodes of the same diameter if good fusion and profile are to be obtained.

Although E6012 electrodes are suitable for welding in all positions, far greater tonnages of it are used in the flat and horizontal positions than in the vertical and overhead positions. They are especially recommended for single-pass, high-speed, high-current horizontal fillet welds. Ease of handling, good weld profile and ability to withstand high current and

to bridge gaps under conditions of poor fit-up make these electrodes very well suited to this type of work. When used for vertical and overhead welding, the electrode size used is frequently one size smaller than would be used if an E6010 or E6011 electrode were used.

These electrodes have been used to advantage on many low-alloy steels, particularly of the higher carbon varieties. This is probably due to the fact that the penetration obtained, although adequate, is by no means that obtained with the E6010 or E6011 types. As a result the pickup of alloying ingredients is not as great, which undoubtedly has a beneficial effect from the standpoint of cracking. Reference to Table 1 will show that far higher currents can be used with this type of electrode than can be used with any other of the all-position electrodes.

The weld metal deposited by these electrodes is lower in ductility and higher in yield strength than weld metal from either E6010 or E6011 electrodes. The mechanical properties to be expected, when welding in accordance with the test procedures prescribed in the Specifications, are shown in Table 2. The chemistry of the deposited metal varies little from that obtained from E6011 electrodes. However, microscopic examination will disclose that the weld metal contains far more nonmetallic inclusions.

EXX13

EXX13 electrodes are used in all positions with a.c. and d.c., reverse polarity. These electrodes were designed originally for light sheet metal work. However, the larger diameters are being used on some applications previously welded with other low-alloy steel or E6012 electrodes.

The coverings used are very similar to the coverings of E6012 electrodes, containing rutile, silicious materials, cellulose, ferromanganese and liquid silicate binders. Easily ionized materials are incorporated in the coating which permits the establishment and maintenance of an arc with a.c. at low welding currents and low open-circuit voltages. These electrodes have a covering known as the *high-titania potassium type*. The necessary alloys in the low-alloy steel electrodes are usually added to the deposit through the covering.

Slag removal is somewhat better with E6013 than with E6012 electrodes and the

Table 1—Current and Voltage Ranges for Mild and Low-Alloy Steel Electrodes

Electrode Diameter, In.	—EXX10 and EXX11— Current, Amp.	Arc Voltage	—E6012— Current, Amp.	Arc Voltage	—EXX13— Current, Amp.	Arc Voltage	—EXX15 and EXX16— Current, Amp.	Arc Voltage	—EXX20 and EXX30— Current, Amp.	Arc Voltage
1/16	20–40	20–22	20–40	17–20	20–40	17–20	...	...	...	...
5/64	25–60	20–22	25–60	17–21	25–60	17–20	...	...	...	...
3/32	30–80	22–24	30–80	17–21	30–80	17–21	70–110	20–22	...	...
1/8	80–120	24–26	80–130	18–22	70–120	18–22	100–150	20–22	100–140	24–28
5/32	120–160	24–26	120–180	18–22	120–170	18–22	135–200	21–23	120–180	26–30
3/16	140–220	26–30	140–250	20–24	140–240	20–24	160–240	22–24	175–250	30–36
7/32	170–250	26–30	170–300	20–24	170–300	21–25	260–320	23–25	200–325	30–36
1/4	200–300	28–32	200–400	20–24	200–350	22–26	300–375	24–27	250–400	30–36
5/16	250–450	28–32	250–500	22–26	250–450	23–27	350–450	24–28	350–450	32–38

NOTE: Currents and voltages nearer the lower limits should be used in the vertical and overhead positions.

Table 2—Mechanical Properties of Mild Steel Weld Metal (As-Welded)

Electrode Classification	Tensile Strength, Psi.	Yield Strength, Psi.	Elongation in 2 In., %	Reduction of Area, %	Impact-Resistance Izod, Ft.-Lb.	Endurance Limit, Psi.	Density, Gm./Cu. Cm.	Brinell Hardness
E6010	62,000-70,000	52,000-58,000	22-28	35	50-70	28,000-32,000	7.82-7.86	140-160
E6011	62,000-73,000	52,000-61,000	22-28	35	50-70	28,000-32,000	7.82-7.86	140-160
E6012	68,000-78,000	55,000-65,000	17-22	25	25-52	Not determined	7.80-7.85	150-170
E6013	68,000-78,000	55,000-65,000	17-22	25	Not determined	Not determined	7.80-7.85	150-170
E6015 and E6016	68,000-76,000	55,000-62,000	22-35	55-75	70-130	Not determined	7.80-7.85	140-160
E6020 and E6030	62,000-68,000	52,000-58,000	25-30	40	50-70	30,000-34,000	7.82-7.85	150-170

arc can be established and maintained more readily, particularly in the case of the small diameters (1/16, 5/64 and 3/32 in.). Even less penetration is obtained than with E6012 electrodes; also the arc action tends to be quieter, the bead surface smoother and with a finer ripple. As in the case of other electrodes, the different brands of EXX13 have varied characteristics. Some of these electrodes are usually recommended for sheet metal applications where their ability to weld satisfactorily in vertical position from the top down is an advantage. Others with a more fluid slag are in part replacing E6012 electrodes for horizontal fillet welds and other general-purpose welding. Rather than the convex type, characteristic of E6012 electrodes, they produce a flat fillet weld similar to that of the E6020 electrodes. They are also readily usable in making butt welds, having a concave bead shape and an easily-removed slag.

Ordinarily the high welding currents which can be used for E6012 electrodes cannot be used for EXX13 electrodes. However the currents and voltages used for both types of electrode will differ little when welding is done in the vertical and overhead positions. Recommended currents and voltages for EXX13 electrodes are shown in Table 1.

The radiographic quality of welds made with EXX13 electrodes is usually good. The mechanical properties of weld metal deposited by E6013 electrodes are shown in Table 2. The chemistry of the deposited metal from E6013 electrodes is very similar to that obtained from E6012 electrodes. However, it is definitely cleaner from the standpoint of slag and oxide inclusions. As previously noted the chemistry and mechanical properties for low-alloy steel weld metal are not given because of differences in chemical requirements, heat treatment, etc.

EXX15

The EXX15 electrodes are made possible by the recent development of a covering low in hydrogen that gives satisfactory operating characteristics and high quality deposits. The electrodes are usually manufactured using a low-carbon (0.10 to 0.14%) rimmed steel core wire having 0.40 to 0.60% manganese, 0.04% max. sulfur, 0.04% max. phosphorus, with a trace of silicon. The covering, consisting largely of minerals of which a

high percentage is soda and lime carbonate, is known as the *low-hydrogen sodium type*. The coverings are slightly thicker than those normal for each diameter of wire, making for slightly more difficult operation due to shortness of the arc which must be maintained.

These are essentially d.c., reverse polarity electrodes and were developed for welding high strength high-carbon and alloy steels in which the ordinary coverings produce a phenomenon known as *underbead cracking*. These underbead cracks occur in the unfused base metal usually just below the center of the weld metal, and are caused by the hydrogen present in conventional electrode coverings. Naturally, the elimination of hydrogen with its consequent underbead cracking permits the welding of *difficult-to-weld steels* if sufficient preheat is used and the preheat temperature maintained until a satisfactory thermal treatment is given. Although these cracks do not occur in ordinary steels, they may occur whenever an ordinary electrode is used on high-tensile steels. Many of the newer high-tensile steels contemplated for future production will require the use of classification EXX15 electrodes. Another use for EXX15 electrodes is the welding of high sulfur steels. The ordinary electrode deposit on these steels (which contain 0.10 to 0.25% sulfur) is badly honeycombed. The EXX15 type of electrode can be used to weld these steels without any difficulty.

The operating characteristics of these electrodes are materially different than electrodes having conventional coverings but compare favorably with stainless steel electrodes having a lime-type covering. The arc is moderately penetrating, the slag heavy, friable and easily removed, and the deposited metal lies in a flat bead or may even be slightly convex. The outstanding operating differences, when compared to conventional electrodes, are a more viscous weld metal which does not permit whipping or fast weaving and a very short arc necessary for low-hydrogen, high-quality deposits. Diameters larger than $^{5}/_{32}$ in. are not generally recommended for vertical and overhead welding. When making vertical and overhead welds, electrodes one diameter smaller than the EXX10 electrode are recommended for a weld of the same size. Diameters larger than $^{5}/_{32}$ in. are recommended for horizontal fillet welds and welds made in the flat position.

These electrodes were developed during the war for the welding of armor plate and in addition to their use on alloy steels, high-carbon steels and high-sulfur steels they have been found useful on malleable iron, on spring steels and for welding the mild steel side of clad plates. Another extensive use has been in the welding of steels which will subsequently be enameled and in all those steels which contain selenium.

Generally speaking, the currents used with these electrodes are higher than those recommended for EXX10 electrodes of the same diameter. Table 1 may not apply to every brand produced but will be found satisfactory for most.

The as-welded mechanical and impact properties of deposits made using E6015 and E6016 electrodes, have been found to be superior to those of E6010 and E6011 electrodes depositing weld metal of the same composition. Numerous tests have indicated the as-welded mechanical and impact properties of deposits from these electrodes approach the properties of stress-relieved deposits from conventional electrodes approach the properties of deposits of conventional electrodes are materially improved when they are stress-relieved, the deposits of low-hydrogen electrodes are changed only slightly. The reduced tendency for underbead cracking and the high quality of as-welded deposits of these electrodes should materially reduce the preheat and postheat of weldments, thus making for better welding conditions and lower thermal treatment costs.

The mechanical properties of deposited metal in the as-welded condition from E6015 electrodes, when the weld is made in accordance with test procedures prescribed in the Specifications, are shown in Table 2. A typical chemical analysis of the deposited metal is 0.08% C, 0.56% Mn and 0.025% silicon.

EXX16

The EXX16 electrodes, having a *low-hydrogen potassium-type* covering, have all of the characteristics of the EXX15 electrodes except that an amount of potassium silicate or other potassium salt is added to the covering to make these electrodes usable with a.c. as well as d.c., reverse polarity. All that has been said

of the EXX15 electrodes applies equally well to EXX16 electrodes.

EXX20

The EXX20 electrodes, having a *high iron oxide sodium-type* covering, are designed to produce flat or slightly concave horizontal fillet welds with either a.c. or d.c., straight polarity and will produce satisfactory fillet and groove welds in the flat position with a.c. or d.c. either or both polarities, depending on the brand. They are characterized by a spray-type arc and a heavy slag, well honeycombed on the underside, which completely covers the deposit and can be readily removed.

When normal welding currents and techniques are employed, penetration is said to be medium. However, these electrodes may be used with high currents, which result in deep penetration, particularly when the deep fillet welding technique is used. Of all types of electrodes produced, EXX20 and EXX30 electrodes are generally considered to be the best for this specialized technique.

EXX20 electrodes are essentially mineral-covered electrodes having a high percentage of iron oxide, manganese compound and silica in the covering along with sufficient alloys to give a deposit of the desired composition. The slag coverage is so extensive and the slag-metal reaction of such a nature that the electrode does not normally depend on gaseous protection. The covering is such that an iron oxide, manganese oxide, silica slag is usually produced. Materials such as alumina, magnesia or sodium oxide may be present to modify the slag. Ferromanganese is used as the main deoxidizer. Sodium silicate is used as the binder. Quantities of basic oxide, acid silica and silicates and deoxidizers must be carefully controlled to produce satisfactory operation and good weld metal. In most cases the core wire employed is the usual 0.10 to 0.14% carbon steel. Some exceptions do exist.

Fillet welds made with EXX20 electrodes tend to have a flat or concave profile and a smooth, even ripple. In many cases the surface of the deposit is dimpled. This characteristic is affected by atmospheric conditions; the more restricted the opening in which the metal is deposited, the greater the tendency toward dimples. It is to be expected in practically all cases on the first few passes of deep groove welds; as the weld nears completion this tendency decreases. Many have noted the fact that the use of a.c. tends to promote this dimpled condition to a greater extent than direct current. No undesirable mechanical or physical defects are associated with this surface condition.

Generally speaking, EXX20 electrodes are recomended for horizontal fillet welds and flat-position welding where the best quality is desired or radiographic standards must be met. High deposition rates can be obtained with high quality on horizontal fillet and groove welds in heavy plate. These electrodes are not generally used on thin sections due to increased warpage resulting from the use of the higher currents usually employed.

The currents and voltages shown in Table 2 may not apply to every brand produced but will be found to be very satisfactory for most. Obviously, when making horizontal fillet welds, using the conventional technique, current values nearer the lower end of the range should be employed if undercutting is to be held to a minimum. If the deep fillet welding technique is employed, higher currents are used.

Applications include pressure vessels, heavy machine bases and structural parts, where thickness of section permits.

The mechanical properties of deposited metal in the as-welded condition from E6020 electrodes, when the weld is made in accordance with the test procedures prescribed in the Specifications, are shown in Table 2.

EXX25 and EXX26

The EXX25 and EXX26 classifications have been created to provide for low-hydrogen electrodes for welding in the flat and horizontal positions. Electrodes conforming to these classifications are not now commercially available. Developments to date indicate that they will deposit weld metal having characteristics similar to those of metal deposited by EXX15 and EXX16 electrodes and will have operating characteristics similar to EXX20 and EXX30 electrodes. The development of E6025 and E6026 electrodes is not contemplated and these classifications have not been established.

EXX30

EXX30 electrodes are for flat-position welding using direct or alternating cur-

rent. Any electrode designed to fulfill the requirements of the EXX20 classifications will also fulfill the requirements of the EXX30 classifications. There are certain other electrodes with which horizontal fillet welding is impractical if not impossible, but which do operate satisfactorily in the flat position and possess some advantages. As a result, the EXX30 classification is necessary.

Since EXX20 electrodes have already been discussed, this discussion will involve only the EXX30 electrodes which have been designed primarily for use in narrow groove butt welds.

The *high iron oxide type* of coverings employed are similar to those of the EXX-20 electrodes except that measures are taken to reduce the amount of fluidity of the slag, thus decreasing the possibility of slag interference in confined spaces. The slag is again essentially an iron oxide, manganese oxide, silica combination with alumina, magnesia and sodium oxide and other modifiers. In some electrodes, substantial amounts of cellulose are present. Ferromanganese is the principal deoxidizer, although other metals and ferroalloys are sometimes used. Again, sodium silicate is used as the binder. As with the EXX20 electrodes, alloys are usually added to the covering to give a deposit of the desired composition. In most cases, the core wire employed is 0.10 to 0.14% carbon steel. Exceptions may exist.

The slag produced, although small in amount and less fluid, is adequate to completely cover the deposit in all passes of groove welds except the last one or two. It tends to be more dense than the EXX20 type, but is just as readily removed. When using direct current, best results are usually obtained with reverse polarity. Generally speaking, this type of electrode is capable of showing higher deposition rates than EXX20 electrodes.

Each layer of flat fillet or butt weld has a concave profile and a smooth, even ripple. The tendency for the surface of the deposit to be dimpled is not as pronounced as in the case of the EXX20 electrodes.

EXX30 electrodes are recomended for welding heavy plate in the flat position only. Applications include pressure vessels, heavy machine bases and structural parts where the thickness of the section permits. Of these, probably the greatest tonnage is used in the construction of pressure vessels where narrow, deep grooves are the rule rather than the exception.

Recommended currents and voltages are the same as for EXX20 as shown in Table 1.

The mechanical properties to be expected from the deposited metal from E6030 electrodes, when deposited in accordance with the test procedures prescribed in the Specifications are identical with those expected of E6020 electrodes. Likewise, the chemistry of the deposited metal is very similar, if not identical. E6030 electrodes, like the E6020 electrodes, are especially useful where rigid radiographic examination must be met.

Table 3 summarizes the usability and operating caracteristics of mild and low-alloy steels discussed in this chapter.

IRON AND STEEL GAS-WELDING RODS

Iron and steel gas-welding rods are designed to give deposited metal of a desired composition. Certain allowances must be made in the composition of the rod for changes which take place during welding. It must be emphasized that the effects of the elements are interrelated and hence may not be treated as individually isolated cases. For example, recovery of such elements as carbon and chromium depends largely upon the amount of deoxidizers such as manganese and silicon which are present. The following discussion of the effects of various elements on the weld puddle and the cooled deposited metal relates to welding rods which contain appreciable amounts of deoxidizers.

Carbon in general, is a strengthening element but causes a corresponding decrease in ductility. In oxy-acetylene welding, carbon may be controlled to a certain extent by adjustment of the welding flame. The use of an oxidizing flame causes reaction of the carbon in the molten weld metal with the excess oxygen, with resultant evolution of carbon monoxide gas which causes lower carbon in the weld and may cause a porous deposit. A reducing flame, on the other hand, introduces carbon into the filler metal as a product of the decomposition of acetylene. In addition, under a reducing flame, carbon is introduced into a narrow surface zone

of the heated base metal, lowering the melting point and resulting in melting less base metal. The recovery of carbon in the range up to 0.20% under a neutral flame is usually 100% provided deoxidizers are present.

Manganese and silicon act as deoxidizers in the molten filler metal. The silicon is the prime deoxidizer and serves to protect carbon and other readily oxidizable additions. Manganese is added to increase the activity of the silicon and to aid in the formation of a fluid slag. In the presence of manganese, silicon becomes a more powerful deoxidizer because of the formation of a stable highly fluid manganese silicate which floats to the surface of the melted metal and serves to prevent appreciable oxidation by the atmosphere surrounding the weld. The viscosity of the slag can be controlled by a proper balance of the manganese and silicon which aids in controlling the weld puddle. Manganese-to-silicon ratios vary from 4:1 to 1.5:1 depending on the intended use of the welding rod. Another advantage of these deoxidizers is that the reflection of light from the slag and the molten steel is different so that laps and incomplete fusion or slag pockets are easily noticed and may be worked out of the puddle. Recovery of the elements varies, but in general about 65% of the manganese and 50% of the silicon present in the rod are recovered in the weld under a neutral flame. Manganese also aids in controlling the effects of sulfur by forming manganese sulfide inclusions.

Phosphorus and sulfur in the welding rod and base metal are retained in the weld metal without much change although there is generally some elimination of sulfur. The specifications set a maximum sulfur content of 0.045% for iron and steel gas-welding rods. Sulfur is particularly harmful when the manganese content is low. In addition, high sulfur is one of the main causes of porosity in weld metal due to evolution of gas which is trapped when the metal solidifies.

Chromium and vanadium are carbide formers which strengthen the weld metal, providing welds with high tensile strength and good ductility. They also tend to aid in the formation of a viscous slag. This is desirable in applications, such as pipe welding where high strength is required and good control of the welding puddle is needed. Recovery of chromium is approximately 80 to 85% of the metal contained in the rod when melted under a neutral flame. Vanadium recovery is approximately 95%. Both elements should be protected by a deoxidizer.

Molybdenum and nickel are both used as strengthening additions. They are transferred from the rod to the weld with no losses and do not appreciably change the characteristics of the molten puddle when present in small amounts. Molyb-

Table 3—Operating Characteristics of Mild Steel and Low-Alloy Steel Electrodes

Classification	Current and Polarity	Welding Positions	Type of Covering	Penetration	Surface Appearance	Slag
EXX10	D. c., reverse polarity (electrode positive)	All	High-cellulose sodium	Deep	Flat, wavy	Thin
EXX11	A.c. or d.c., reverse polarity (electrode positive)	All	High-cellulose potassium	Deep	Flat, wavy	Thin
E6012	D.c., straight polarity (electrode negative) or a.c.	All	High-titania sodium	Medium	Convex, rippled	Heavy
EXX13	A.c. or d.c., straight polarity (electrode negative)	All	High-titania potassium	Shallow	Flat or concave, slight ripple	Medium
EXX15	D.c., reverse polarity (electrode positive)	All	Low hydrogen sodium	Medium	Flat, wavy	Medium
EXX16	A.c. or d.c., reverse polarity (electrode positive)	All	Low-hydrogen potassium	Medium	Flat, wavy	Medium
EXX20	D.c., straight polarity (electrode negative) or a.c. for H-fillets; d.c., either polarity or a.c. for flat position welding	H-Fillets and flat	High iron oxide	Medium	Flat or concave, smooth	Heavy
EXX30	D.c., either polarity or a.c.	Flat only	High iron oxide	Shallow	Flat, smooth	Heavy

denum helps to prevent hot cracking, while nickel in amounts up to 1% causes a more fluid puddle.

Recent work indicates that excessive heating during the welding operation adversely influences the impact strength of gas welds. It has been suggested that the use of special alloy welding rods not subject to excessive grain growth will partially overcome the effects of overheating and improve the impact properties of the welds. Low impact strength also may be corrected by depositing the weld metal in a number of small string beads instead of wide weave beads. The work indicates the need for use of welding rods of special composition for all weldments requiring good impact strength.

ALUMINUM AND ALUMINUM-ALLOY FILLER METAL

On thin material (less than $^1/_{16}$-in. thick) the base material is frequently flanged and the flange melted into the joint as a source of filler metal. On heavier materials, welding rod in the form of wire is almost universally applied. Commercially pure aluminum and aluminum-manganese alloy are welded with commercially pure aluminum wire. General-purpose welding on other aluminum alloys is done with 95% Al–5% Si alloy wire. These two alloys are standard and are used except where special filler metal must be used to obtain resistance to specific chemicals or to match colors on parts that are processed with subsequent oxide coatings. Such cases usually require testing of special filler metal and consultation with the manufacturer of the parent alloy is suggested.

The use of high purity aluminum to obtain resistance to certain types of chemical attack is frequently encountered. In those cases, use of filler metal of at least as high purity as the parent material is essential to obtain maximum resistance to corrosion in the welded joints.

Arc Welding

Shielded metal-arc welding is usually done with covered electrodes conforming to AWS-ASTM *Specifications for Aluminum and Aluminum Alloy Metal-Arc Welding Electrodes* (see Chapter 61). These specifications cover electrodes of commercially pure aluminum and the 95% Al–5% Si alloy; the latter is the most commonly used for general-purpose work. Electrodes may be obtained in any composition desired to suit specific requirements of a job.

Aluminum and aluminum-alloy metal-arc welding electrodes have been developed for use with direct current preferably in the flat position although some welding is done in the vertical position. Which polarity to use is determined by test or experience for each joint.

Other metal-arc welding processes, including carbon-arc, inert-gas metal-arc and atomic-hydrogen welding, involve th use of welding rods of the same compositions as described above, except that the rods are not coated and, except for inert-gas metal-arc welding, a suitable flux must be used.

Gas Welding

Gas-welding rods are usually of either pure aluminum or the 95% Al–5% Si alloy with rods of special analyses used as required for specific applications. A suitable flux is always used.

Foundry Welding of Castings

All of the welding processes are used in the foundry for salvaging cast parts that have local defects such as misruns, porous or unsound spots, or lack of filling on bosses and ribs. In this case, filler metal of the same composition as the base metal is almost universally used for welding. Frequently, the foundry will make cast welding rod for this purpose although filler metal of the same composition as many of the standard and frequently used casting alloys is available.

CORROSION-RESISTING CHROMIUM AND CHROMIUM-NICKEL ELECTRODES

Arc-welding electrodes which deposit ferrous weld metal containing more than 4% chromium and less than 50% nickel are considered within the scope of AWS-ASTM *Specifications for Corrosion Resisting Chromium and Chromium-Nickel Electrodes*. Because of the corrosion- and heat-resisting properties of these alloys, the specifications are frequently referred to as the *stainless electrode specifications*.

The tests required by these specifications classify the electrodes, first, as to composition, and second, as to usable posi-

tions of welding. By standardizing the weld metal compositions, which are determined by chemical analysis, uniformity of service performance in corrosion resistance is assured. Interchangeability of electrode brands having the same series number is assured by requiring them to meet usability standards in various welding positions and to pass an all-weld-metal tension test for quality.

Weld Metal Compositions

Over the past thirty years, the development of stainless steels in various laboratories has resulted in many different compositions most of which are readily weldable and require suitable arc-welding electrodes. Fortunately a single electrode composition is generally suitable for welding a variety of stainless steels. Chapters 30 and 31A indicate the variety of stainless steel base metals which are presently standardized by the steel suppliers.

The electrodes covered by the specifications are classified as to composition as follows:

E308 Electrodes.—By far the greatest amount of stainless electrodes used conforms to this series of classifications commonly designated the *19–9* electrodes. The familiar 18–8 chromium-nickel alloy has many modifications which are welded with the E308 electrodes. By specifying that the weld metal shall have a suitable maximum carbon content and suitable minimum chromium and nickel contents, the E308 electrodes can be used for all AISI wrought stainless steels—Types 301 to 308 inclusive—and for the ACI Casting Types CF-8, CF-20 and HF.

E309 Electrodes.—For more rigid service requirements where higher chromium and nickel contents are required, this so-called *25–12* electrode is applicable. Its composition corresponds to that of wrought stainless steel of Type 309 and the CG-12, CH-10, CH-20 and HH castings. Occasionally for specific applications, columbium is added to stabilize the alloy, in which case the E309 electrode should be similarly modified. Because of its higher alloy content it is frequently employed in welding 18–8 clad steels so that the fusion with the mild steel backing will not dilute the weld metal composition below that of the alloy cladding.

E310 Electrodes.—These very popular, so-called *25–20* electrodes, are used more for special applications than for welding the corresponding wrought Type 310 and cast CK–20 and HK steels. When used for welding carbon steels or low-alloy steels, a strong and ductile weld is obtained. For this reason, these electrodes have been used widely for welding armor plate, particularly naval armor in heavy sections. The welding of low-alloy, hardenable steels with this type of electrode is simplified by the fact that it is usually unnecessary to use preheat or postheat treatment, even for very hardenable steels. These electrodes are also used for joining stainless to mild steel and stainless clad steels. For molybdenum- or columbium-bearing stainless clad steel, modified E310 electrodes are made by introducing the required molybdenum or columbium through the electrode covering.

E316 and E317 Electrodes.—The introduction of molybdenum to ordinary 18–8 stainless steel makes the alloy more resistant to the corrosive attack of many organic acids, brine and sulfurous and sulfuric acids. Two molybdenum alloys are standard, one containing about 2% and the other from 3 to 4% molybdenum. For this reason two electrodes are specified to match the compositions of the corresponding wrought alloys, Types 316 and 317. The E316 electrodes are also applicable for welding the cast CF–8M and CF–12M alloys. Besides improving the corrosion resistance, the introduction of molybdenum gives the alloy improved creep properties at elevated temperatures. Occasionally E316 electrodes are applicable for certain welds involving the so-called *superalloys* used in gas turbines; for such applications, however, special electrode compositions containing tungsten, columbium, molybdenum and cobalt are usually required. Stabilized Type 316 alloys containing columbium (now designated Type 318) are available which are welded with comparable electrodes with columbium added through the coating. Stabilization is also being accomplished by reducing the carbon content to below 0.03% and for such steel the columbium-bearing electrodes are usually recommended.

E330 Electrodes.—The iron-base alloy having the highest nickel content is the Type 330 alloy containing 15 Cr–35 Ni. This alloy is more frequently supplied in cast form, designated HT, than the wrought Type 330 and is popular for fur-

nace parts and other heat and scale-resisting applications. The use of E330 electrodes is usually limited to the welding of similar compositions.

E347 Electrodes.—The introduction of columbium or titanium for the stabilization of austenitic alloys against intergranular corrosion is discussed in Chapter 31. E347 electrodes match the composition of the columbium-stabilized stainless steels, designated as Type 347 in wrought form and CF–8C in cast form. They are also used for welding the titanium-stabilized steels, Type 321, since titanium-bearing electrodes are virtually unavailable due to the extreme difficulty in transferring sufficient titanium across the arc for stabilization purposes. Equally satisfactory E347 electrodes are prepared in either of two ways: the core wire may be Type 308 (without columbium) with the required columbium added through the electrode covering, or the core wire may be Type 347 (having somewhat higher than normal columbium to compensate for arc losses) on which a standard covering is applied.

Table 4—Usable Positions and Types of Current for Chromium and Chromium-Nickel Electrodes

Usability Designation	Direct Current		Alternating Current	
	Flat and Horizontal Fillet	Vertical and Overhead	Flat and Horizontal Fillet	Vertical and Overhead
-15	All sizes	5/32 in. and smaller	Not recommended	Not recommended
-16	All sizes	5/32 in. and smaller	All sizes	5/32 in. and smaller
-25	All sizes	Not recommended	Not recommended	Not recommended
-26	All sizes	Not recommended	All sizes	Not recommended

E410 Electrodes.—The 12% chromium steel is the lowest alloy steel which is within the commonly considered stainless steel group. It is a hardenable steel and popular for many corrosion and elevated temperature applications, such as in power plants and petroleum refineries. The E410 electrodes when used to weld Types 405, 410 and 414 wrought steels and Type CA–15 cast steel require preheat and postheat treatments for most engineering purposes. Frequently electrodes of this classification are used for surfacing mild steel parts to resist corrosion, erosion and abrasion, such as occur in valve seats and other valve parts.

E430 Electrodes.—Type 430 wrought steel is most frequently employed for its corrosion-resistance to oxidizing mineral acids such as nitric acid. The chromium content is usually between 15 and 17%, and with its low carbon content, the alloy consists of martensite and nonhardenable ferrite. As the chromium increases, the non-hardenable ferrite constituent increases and the strength, ductility and impact properties suffer, while the corrosion resistance improves. A satisfactory balance for many applications is achieved at about 16% chromium, and consequently this is one of the most widely used of the straight chromium steels. Because of its partially hardenable nature, preheat and a postheat treatment must be applied when welding with E430 electrodes. Electrodes having higher chromium contents, up to 28% are also available but because of their limited application they have not been included in the specifications.

E502 Electrodes.—Although not a stainless steel in the usual sense, the 5% chromium-molybdenum steel is widely used in refinery pipe lines for its corrosion resistance to hot, sour, crude oils and its strength at elevated temperatures. It is an extremely hardenable steel and therefore preheat and postheat treatments are required when welding with E502 electrodes. For increased corrosion resistance the chromium may be increased, resulting in two modifications, one containing about 7% and the other about 9% chromium. Electrodes are also available for both of these steels.

Usability Characteristics and Types of Coverings

The Specifications recognize the various types of coverings by requiring a fillet-weld test in all of the usable conditions and with each usable type of current. Four usability classifications, as shown in Table 4, are thus defined, each designated by a two-digit number following the composition designation (e.g. E308–15).

The terms *lime, lime-titania* and *titania* are frequently used to designate various types of coverings for stainless electrodes. In general, a lime-type covering is one whose mineral ingredients comprise chiefly limestone and fluorspar with only minor amounts (up to about 8%) of titanium dioxide. Coverings containing more than 20% titanium dioxide are usually considered as the titania type and those between 8 and 20% are considered to be the lime-titania type.

Lime Type.—The basic lime type covering is usually applicable for electrodes operating on d.c., reverse polarity only. In the flat position, the bead ripples are less uniformly spaced and the fillet weld contours are more convex than with the titania type. In the vertical position this type of electrode is usually preferred because smooth uniform welds can be made easily. Fully austenitic chromium-nickel welds from lime-type electrodes show considerably less tendency to crack or fissure than those from titania-type electrodes. The -15 classification is usually applicable to lime-type covered electrodes.

Titania Type.—For a.c. welding, the covering always contains some titania, usually sufficient to classify it as a titania type. In addition, readily ionizing elements, such as potassium, are added for arc stability. Such electrodes are designated a.c.-d.c. electrodes, and although adjusted to make them usable with a.c., they are more frequently used with d.c., reverse polarity. They are used in preference to the lime-type electrodes for flat-position welding, particularly for smooth concave fillet welds or for butt welds which require finish grinding, because of the ease with which the welder can deposit uniform metal with a minimum of reinforcement. If they qualify as an all-position electrode, they may be designated -16; otherwise they fall in the -26 classification.

Titania-type electrodes are also available for d.c., reverse polarity only. They are usually designed to meet the -25 classification for use only in the flat and horizontal fillet positions, so that full advantage can be taken of the characteristics imparted by the titania minerals.

Lime-Titania Type.—This covering type is more often applied to the straight chromium or chromium-molybdenum steels than to the chromium-nickel steels. Depending on the remaining ingredients, electrodes with this type of covering may be used with d.c. only or on both a.c. and d.c.; they may be all-position electrodes or restricted for use in the flat position.

Tables of usable currents and voltages are not incorporated for they may vary widely for different brands conforming to the same classification.

Mechanical Properties

The specifications specify minimum tensile strength and elongation for each electrode. All-weld-metal tension specimens are specified because the properties of the weld metal thus determined are uninfluenced by the characteristics of the base metal. The properties of the chromium-nickel alloys are usually tested in the as-welded conditions and the straight chromium or chromium-molybdenum steels are usually tested after suitable postheat treatments. Typical mechanical properties are shown in Table 5.

Table 5—Typical Mechanical Properties of Chromium and Chromium-Nickel Weld Metal[a] (All-Weld-Metal Specimens)

	E308	E309	E310	E316	E330	E347	E410[b]	E430[b]	E502[b]
Yield strength, psi.	58,000	58,000	55,000	55,000	52,000	60,000	45,000	53,000	34,000
Ultimate strength, psi.	88,000	88,000	85,000	82,000	85,000	90,000	80,000	80,000	72,000
Elongation in 2 in., %	40	40	40	40	35	35	32	27	35
Reduction in area, %	50	50	45	45	45	45	65	65	65
Brinell hardness	150	150	150	150	150	160	160	165	130

[a] As-welded, except as indicated.
[b] After heat treatments as follows:
E410—1550 to 1650°F. for 2 hr., furnace cooled 50° per hr. to 1100°F., air-cooled.
E430—1400 to 1450°F. for 4 hr., furnace cooled 100° per hr. to 1000°F., air-cooled.
E502—1550°F. for 2 hr., furnace cooled 50° per hr. to 1200°F., air-cooled.

Corrosion Resistance

In the annealed condition, stainless steel weld metal is usually comparable to wrought or cast stainless steel from

the standpoint of corrosion resistance. In many applications, however, welds are placed in corrosion-resisting service in the as-welded or in the stress-relieved (or stabilized) condition. Certain corrosive media may attack the welds more rapidly than the base metal, so that unless service experience is already available, it is usually desirable to conduct some type of corrosion test of the welds. The commonly used tests are described in Chapter 31A. Typical corrosion test data on all-weld-metal specimens subjected to the Huey (boiling 65% nitric acid) Test are given in Table 6.

Table 6—Typical Corrosion Rates of Corrosion-Resisting Weld Metal in Boiling 65% Nitric Acid

Average of Five 48-Hr. Periods; Penetration per Month, In.

	E308	E316	E347	E430
As-welded	0.0013	0.0015	0.0010	....
Sensitized[a]	0.0151	0.020	0.0051	....
Quench anneal[b]	0.0006	0.0008	0.0007	....
Subcritical anneal[c]	....	....	....	0.0045

[a] 1200°F. for 4 hr., air-cooled.
[b] 1950°F. for 15 min., water-quenched.
[c] 1450°F. for 4 hr., furnace-cooled 100°F. per hr. to 1000°F., air-cooled.

CORROSION-RESISTING CHROMIUM AND CHROMIUM-NICKEL WELDING RODS

The oxy-acetylene, atomic-hydrogen, inert-gas and submerged-arc welding processes are all applicable to joining chromium-nickel and straight chromium steels and frequently require added filler metal. Welding rod in the form of wire varying from $^1/_{16}$ to $^3/_{16}$ in. in diam., straightened and cut to 36-in. lengths, is supplied for these welding processes. For submerged-arc welding, coils of wire weighing from 20 to 50 lb. and from 12 to 20 in. in diam. are usually specified.

The composition of the wire for welding rods is generally comparable to that used for electrode core wire. Since the wire is furnished without a covering, all of the alloying elements required in the weld metal must be present in the wire. If unusual losses of elements occur during welding, compensation for these losses must be supplied by increasing the alloy content of the wire.

For submerged-arc welding involving materials of similar composition, the core wire may be of comparable composition, but it usually contains somewhat higher chromium to compensate for oxidation losses. When dissimilar metals are welded such as stainless steel to mild steel or to stainless clad steel, not only the oxidation losses but also the dilution losses must be considered in selecting the welding rod alloy. Chromium oxidation losses have been estimated at about 10% of the chromium content, assuming equal chromium oxidation in the fused base metal and in the filler metal. For estimating dilution effects, the amount of fused base metal must be determined. These welding rods are not presently covered by any AWS-ASTM filler-metal specification.

NICKEL AND HIGH-NICKEL ALLOY FILLER METAL

General

This section deals with filler metals containing over 50% nickel. They are normally used to join nickel and the high-nickel alloys described in Chapter 35, either to themselves or in dissimilar metal combinations. Nickel or Monel filler material is also used to join cast iron to itself or to other metals.

A filler material having the same nominal composition as the base material to be welded is usually selected. In welding dissimilar metal combinations, a filler material having compatible metallurgical characteristics is essential.

Coated arc-welding electrodes are available in sizes ranging from $^5/_{64}$ (or 0.075) to $^3/_{16}$ inch. Diameters of $^1/_4$ in. or larger are available in some alloys, but their use is generally limited to surfacing applications.

Welding rods for gas welding, atomic hydrogen welding, inert-gas metal-arc or submerged-arc welding are available in varying sizes from 0.035 to $^1/_4$ in. in straight 36-in. lengths or in coils.

AWS-ASTM specifications for nickel and nickel-alloy filler metal were not available at the time this section was being written; in their absence, the following paragraphs will discuss nickel and nickel-alloy filler material, classifying each on the basis of nominal composition of the core wire.

Nickel

Nickel arc-welding electrodes are used for welding nickel, Duranickel, and nickel-clad steels to themselves or to carbon steel, stainless steel and other nickel alloys. They are used also to join copper-containing alloys like Monel or 70/30 cupro-nickel to a ferrous material like carbon steel or stainless steel. Nickel electrodes are designed for use with d.c., reverse polarity and can be used in all welding positions. The molten weld metal under the arc is not extremely fluid but must be manipulated very skilfully to obtain proper weld contour; in this respect nickel electrodes are unlike carbon steel and stainless steel electrodes. The resulting weld will have more pronounced ripples than are formed in steel welds, but if properly made, will be sound and have mechanical properties similar to those of annealed nickel plate material. The weld metal cannot be age-hardened by heat treatment therefore welds in Duranickel will not respond to heat treatment as does the base material.

Nickel welding rods are used, without flux, to gas weld nickel to itself or to steels or stainless steels. A reducing flame is employed (excess acetylene). Welding rods are also produced specifically for atomic-hydrogen welding and for inert-gas metal-arc welding. Nickel welding rod in coils is used in submerged arc welding of nickel with clean, commercially obtainable fluxes.

Monel

Monel arc-welding electrodes are used for joining Monel to itself or to copper-nickel alloys, "R" Monel or "KR" Monel. These electrodes are designed for use with d.c., reverse polarity, and can be used in all welding positions. These electrodes have a modified spray-type arc with surprisingly deep penetration qualities. The molten weld metal under the arc is quite fluid and good weld contours are obtained easily. A special Monel electrode for joining Monel to carbon, stainless or Monel-clad steel without cracking is available. Deposited Monel weld metal is slightly harder and stronger than annealed Monel plate material, but it cannot be hardened by heat treatment.

Monel welding rods are available for gas welding Monel to itself or to other nickel-copper alloys. A flux is recommended and a reducing flame is employed. Monel welding rods are used also as filler material for atomic hydrogen, inert-gas metal-arc welding and submerged arc welding. A clean commercial flux is used with submerged arc welding.

Nickel and Monel Electrodes for Welding Cast Iron

Nickel- and nickel-alloy-cored electrodes are available for welding cast iron or for joining cast iron to other ferrous materials or to nickel alloys. These are available for use with either d.c. or a.c. and can be used in any welding position. The arcing characteristics and the ease of handling of these electrodes are exceptionally good, comparing very favorably with other types of electrodes. The resulting weld deposits contain considerable iron and carbon and are not as ductile as nickel weld metal, but are sufficiently ductile as compared to cast iron. These electrodes should never be used for joining nickel or nickel alloys to themselves.

In the past, Monel-cored electrodes have been used for welding cast iron. While they still are being used to a limited extent, the cracking phenomenon occurring when ferrous materials are melted together with copper-containing materials is an ever-present liability. The nickel-cored welding electrodes described above are considerably more satisfactory.

"K" Monel

"K" Monel arc-welding electrodes and welding rods are available for welding of "K" Monel. In operation, they behave much like Monel electrodes with the exception that the weld deposit will respond to heat treatment.

Inconel

Inconel arc-welding electrodes are designed for use with d.c. or a.c. and for all-position welding. They are used for joining both Inconel and Inconel "X" to themselves or to stainless steels. The arcing characteristics of Inconel electrodes are excellent and similar to those of austenitic stainless steels.

Inconel welding rods are used with a boron-free flux and a slightly reducing flame in gas welding for the same applications as the arc-welding electrodes. Inconel welding rods are used for automatic submerged arc welding with commercially obtainable flux.

80/20 Nickel-Chromium

Arc-welding electrodes of 80% nickel–20% chromium are designed for use with d.c. or a.c. and can be used in all welding positions. They are used for joining 80% nickel–20% chromium alloy and other similar nickel-chromium materials, as well as for joining Inconel and Inconel "X" to steel.

They are particularly useful in welding the Inconel side of Inconel-clad steels. The pickup of iron by dilution of the molten weld metal with steel of the backing material produces a chemical composition similar to that of the original Inconel.

Other Nickel-Chromium Compositions

Arc-welding electrodes are available for joining other nickel-chromium heat-resisting alloys; thereby the chemical compositions of the deposited material matches those of the materials welded. Most of these electrodes are designed for use with d.c., reverse polarity and can be used in all welding positions.

Hastelloys

Welding rods and electrodes of the same nominal chemical composition as the base metal are used for oxy-acetylene or arc welding the Hastelloy alloys.

Hastelloy alloy welding rods are generally used with a special flux and are applied with a slightly reducing flame in oxy-acetylene welding; they are used also as filler metal for atomic hydrogen and for inert-gas metal-arc welding.

Hastelloy alloy electrodes are designed for use with d.c., reverse polarity. These electrodes can be used in all welding positions, but, since the molten weld metal under the arc is not particularly fluid, it must be manipulated with care to obtain a proper weld contour. Welding rods of Hastelloy Alloys *B* and *C* are also available for use in submerged arc welding. These filler metals may be used to join the Hastelloy alloys to themselves or to ferrous or stainless materials.

Illium

Coated Illium arc-welding electrodes are available in one size only, $^1/_8$-in. diam. by 18 in. long. Cast Illium gas-welding rods are available in all of the standard sizes for welding the Illium alloys. They are of the same nominal composition as the base material to be welded. The arc-welding electrodes are designed for use with d.c., reverse polarity. The welding rods are used with a slightly reducing flame, and a cast-iron-type flux.

COPPER AND COPPER-ALLOY ARC-WELDING ELECTRODES

Copper and copper-alloy electrodes conforming to the AWS-ASTM *Specifications for Copper and Copper-Alloy Metal-Arc Welding Electrodes* are listed in Table 7, which includes the common names and the minimum mechanical properties of the classifications established by the foregoing specifications. The chemical analyses of these electrodes will be found in Table 1 of the specifications in Chapter 61.

A discussion of each of the classifications follows.

Copper (ECu)

Copper electrodes are made with deoxidized-copper core wire. The copper is usually deoxidized with phosphorus, but silicon or other metals may be used. These electrodes are used for welding electrolytic or deoxidized copper when the weld metal must closely match the properties of the base metal. Welds will generally equal wrought copper in their corrosion resistance. The electrical conductivity of the weld metal is about equal to deoxidized copper or 75% of electrolytic copper. The strength and elongation of the weld metal can be improved by cold-working, peening or rolling, followed by annealing at 900 to 1000°F. for a few minutes.

Electrolytic copper has the highest heat conductivity of all the commonly used metals. Deoxidized copper is next, with 75 to 85% of the conductivity of electrolytic copper. In order to shielded metal-arc weld these metals with ECu electrodes, it is necessary to preheat the weld zone from 800 to 1000°F. The joint should be prepared with a 90-deg. vee groove, a wide root opening and a copper or carbon backing.

Most ECu electrodes are designed to work on d.c., reverse polarity. The current used is always higher than would normally be required for carbon steel electrodes of the same diameter. The electrode manufacturer's recommendations for current and voltage should be followed.

Phosphor Bronze A (ECuSn-A)

These low-tin, copper-alloy electrodes contain about 5% tin and are deoxidized with phosphorus. They are commonly used for welding copper, bronze, brass and occasionally, for overlaying steel. ECuSn-A electrodes are also used for welding cast iron. The weld metal has a tensile strength of 40,000 psi. which provides a margin of safety for welding copper, where the presence of tin in the weld metal is not objectionable.

When welding copper with ECuSn-A electrodes, the work should be preheated to about 700°F.; for surfacing steel, about 500°F. preheat is satisfactory; on phosphor bronze, 300 to 400°F. is satisfactory.

Table 7—Mechanical Properties of Copper and Copper-Alloy Electrodes

Common Name	AWS-ASTM Class	Mechanical Properties: Melting Point, °F.	Tensile Strength, Min., Psi.	Yield Strength 0.5% Ext., Min., Psi.	Elongation, in 2 In., %	Brinell Hardness
Copper	ECu	1972	25,000	Not specified	20	Not specified
Phosphor Bronze A	ECuSn-A	1922	40,000	20,000	15	70 to 85 (500 kg.)
Phosphor Bronze C	ECuSn-C	1880	45,000	25,000	12	85–100 (500 kg.)
Copper-nickel	ECuNi	2237	45,000	25,000	25	Not specified
Copper-silicon	ECuSi	1866	40,000	20,000	20	80–100 (500 kg.)
Aluminum bronze	ECuAl-A	1910	65,000	30,000	15	130–160 (3000 kg.)
Aluminum bronze	ECuAl-B	1905	70,000	35,000	10	160–210 (3000 kg.)
Aluminum bronze	ECuAl-C	1900	75,000	40,000	4	210–260 (3000 kg.)
Aluminum bronze	ECuAl-D	1895	65,000	45,000	Not specified	260–310 (3000 kg.)
Aluminum bronze	ECuAl-E	1890	70,000	50,000	Not specified	310–365 (3000 kg.)

ECuSn-A electrodes are designed for both d.c. and a.c. operation. The current used depends on the base metal, its thickness and the amount of preheat. Manufacturers' recommendations as to current and voltage should be followed.

Phosphor Bronze C (ECuSn-C)

These electrodes nominally contain 8% tin. They are generally used for the same type of work as the ECuSn-A electrodes. Their better strength and higher hardness make them preferable for welding the higher strength bronzes and for overlaying steel. Welding procedures are the same as for ECuSn-A electrodes.

Copper-Nickel (ECuNi)

The copper-nickel electrodes are nominally 70% copper and 30% nickel and were developed primarily for welding copper-nickel base metals. The weld metal develops approximately the same strength as annealed copper-nickel plates or sheets.

When shielded metal-arc welding thin sheets, a copper backing is used. For heavier sections, a 60-deg. vee groove is satisfactory although a double-vee groove is preferred. The copper-nickel alloys are hot-short, so preheating should not be used. The interpass temperature should be kept below 150°F.

ECuNi electrodes are used with d.c., reverse polarity. Manufacturer's recommendations for values of current and voltages should be followed.

Copper-Silicon (ECuSi)

The copper-silicon alloys are often referred to as silicon-bronzes. The core wire of coated electrodes is nominally 94% copper, 3% silicon and 1% manganese, iron or tin. The tensile strength of the deposited metal is slightly lower than that of annealed sheets, unless considerable care is taken in selecting the welding procedure. The yield strength of the weld metal is usually equal to that of soft sheets and plates.

Thin copper-silicon sheets require a copper backing. Heavier sections are beveled to form a 60-deg. vee and a double-vee is used whenever possible.

Copper-silicon electrodes are used with d.c., reverse polarity. The manufacturer's

recommendations for values of current and voltage should be followed.

Aluminum Bronze (ECuAl-A)

This aluminum bronze is nominally an alloy of 8% aluminum, 1% iron and the balance copper. It is the most ductile of the aluminum bronzes. This ductility, combined with good yield and ultimate strengths makes it particularly suitable for welding aluminum-bronze sheet and plate and manganese-bronze castings. It is well suited to joining dissimilar metals and for applying corrosion and wear-resistant overlays.

Like other copper-alloy weld metals, aluminum bronze is quite fluid when molten, so thin sections are welded with a backing of copper or metal similar to that being welded. A 60-deg. vee groove angle and a $^1/_8$-in. root opening are used for heavy sections; a U-groove having the same groove angle and a $^1/_4$-in. groove radius is used where a root opening cannot be provided. A double groove is preferred, if it is possible to weld from both sides. The surfaces being welded must be dry and free from oxides and grease. Aluminum-bronze electrodes are generally used with d.c., reverse polarity, but some are coated for use on alternating current. For best deposit efficiency, use the electrodes on the low side of the current range recommended by the manufacturer.

Aluminum Bronze (ECuAl-B)

ECuAl-B is a copper alloy containing 9 to 10% aluminum and 3 to 5% iron. Of the five aluminum-bronze alloys, ECuAl-B has the highest strength combined with reasonably good ductility. It is used for fabricating aluminum-bronze weldments and for overlays on bearing surfaces where moderate hardness is desired.

The welding procedure for ECuAl-B electrodes is similar to that for ECuAl-A.

Aluminum Bronze (ECuAl-C)

This aluminum bronze contains 10 to 11% aluminum and 3 to 5% iron. ECuAl-C has the highest strength of the aluminum bronzes. It is used for bearing overlays working against hardened steel and for building up worn aluminum-bronze bearings of similar analysis.

Because of the lower ductility of ECuAl-C weld metal, preheating from 700 to 800°F. is recommended when welding aluminum-bronze castings. Other welding characteristics are similar to ECuAl-A.

Aluminum-Bronze (ECuAl-D)

ECuAl-D aluminum bronze contains 11 to 12% aluminum and 3 to 5% iron. It is a metal similar to ECuAl-C except for higher hardness, 260 to 310 Brinell (3000kg.), and slightly lower strength. The applications for this metal and the welding procedure are the same as those for ECuAl-C.

Aluminum Bronze (ECuAl-E)

This aluminum bronze, of maximum hardness, contains 12 to 13% aluminum and 3 to 5% iron. The deposited weld metal has a hardness of 310 to 365 Brinell. It is an excellent bearing metal and has great wear resistance. These properties make it particularly suitable for surfacing drawing and forming dies.

The welding procedure for ECuAl-E electrodes is the same as for ECuAl-C.

COPPER AND COPPER-ALLOY WELDING RODS

Copper and copper-alloy welding rods are listed in Table 8. This table shows the common names of the alloys, the AWS-ASTM designations, the nominal compositions and the minimum mechanical properties. While no welding rod specifications have been issued, it is expected that the classifications will follow the pattern established by the electrode specifications.

Copper (GCu)

The principal requirement for copper welding rods is that they deposit weld metal which matches the corrosion resistance of wrought electrolytic or deoxidized copper. This is generally the case, if the copper plus silver content of the rod is not less than 98.5%. Small amounts of tin, manganese, silicon or phosphorus may be present to improve the strength and deoxidize the weld metal. These small additions of metals, however, may reduce the electrical conductivity of the weld metal to 70% of that of electrolytic copper. If the electrical conductivity of the weld metal is of prime importance, then electrolytic copper welding rod should be used.

GCu welding rods are generally used

for oxy-acetylene or inert-gas metal-arc welding. These high copper alloys seldom contain enough deoxidizers to stand the high temperature of the carbon arc. For oxy-acetylene welding, a slightly oxidizing flame is used. To determine the amount of excess oxygen to use, a few drops should be melted off the end of the copper rod onto a clean brick, carbon block, cold piece of steel or cast iron. When this metal is heated with a reducing or excess-acetylene flame, boiling or bubbling will be seen and the metal may become gassed. The oxygen in the flame is slowly increased until the molten metal lies quietly under a thin film of oxide. The deoxidizer in the rod will prevent oxidation of the metal under the oxide film. The use of a welding flux will reduce the amount of excess oxygen required in the flame, but may interfere with the deposition of the weld metal in multi-layer welds.

Copper up to $^{3}/_{16}$-in. thick may be butt welded with a square groove and a root opening of about one-half the thickness of the base metal. For material $^{3}/_{16}$ through $^{3}/_{8}$-in. thick, a single 90 deg. vee groove with a $^{1}/_{16}$-in. root face is recommended. For material over $^{3}/_{8}$-in. thick, a 90-deg. double-vee should be used, if it is possible to weld from both sides. A backing of carbon or heavy copper is helpful; if a copper backing is used, narrow shims under the plates being welded will prevent the backing from chilling the weld area.

Backhand welding is generally best when oxy-acetylene or inert-gas arc-welding copper over $^{1}/_{8}$-in. thick. A large oxy-acetylene tip with low gas pressures should be used and the cone of the flame kept away from the weld pool so that the flame will not blow the weld metal out of the groove. Continuous preheating with another torch is required when welding copper over $^{1}/_{4}$-in. thick.

Copper Silicon (GCuSi)

Copper-silicon alloy welding rods contain about 3% silicon, 1% tin, manganese or iron, and the balance copper. They are most commonly used for welding copper-silicon sheet and plate and for welding copper. The strength of the weld metal approximates that of soft copper-silicon plate or almost twice that of annealed copper. The corrosion resistance is generally equal to copper but its elec-

Table 8—Compositions and Mechanical Properties of Copper and Copper-Alloy Welding Rods

Common Name	AWS-ASTM Class[a]	Composition, %								Mechanical Properties				
		Cu	Zn	Sn	Mn	Fe	Si	Ni	P	Melting Point, °F.	Min. Tensile Strength, Psi.	Min. Yield Strength, Psi.	Min. Elongation in 2-in. %	Brinell Hardness
Copper	GCu	98.5 incl. silver	....	1.0 max.	0.50 max.	....	0.50 max.	....	0.05 max.	1972	25,000	7,500	20	Rockwell F 25
Copper-silicon	GCuSi	94.0 min.	....	Not specified	Not specified	Not specified	2.5–3.75	Not specified	....	1866	50,000	20,000	25	80–100 (500 kg.)
Phosphor Bronze A	GCuSn-A	93.0 min.	....	4.0–6.0	.....	....	....	....	0.3 max.	1922	40,000	20,000	15	70–85 (500 kg.)
Phosphor Bronze D	GCuSn-D	88.5 min.	....	9.5–11.5	.....	....	....	....	0.3 max.	1832	45,000	25,000	12	90–110 (500 kg.)
Copper-nickel	GCuNi	67.0 min.	.....	....	....	....	....	29.0 min	Others 4.0 max.	2237	45,000	25,000	25	Not specified
Naval bronze	GCuZn-A	59.0 min.	39.0 min.	0.50–1.0	.....	.....	....	....	.....	1625	50,000	20,000	25	70–90 (500 kg.)
Manganese bronze	GCuZn-B	58.0 min.	38 min.	0–1.00	0.25–1.00	0.25–1.00	.....	....	.....	1598	55,000	22,000	20	80–10.g (500 kg.)
Low-fuming bronze	GCuZn-C	58.0 min.	38 min.	0–1.00	0.25–1.00	0.25–1.00	0.10 max.	.....	.....	1598	55,000	22,000	20	80–100 (500 kg.)
Nickel bronze	GCuZn-D	45.0 min.	40.0–44.5	.....	.....	.....	Not specified	9.0–11.0	Not specified	1690	60,000	25,000	10	90–110 (500 kg.)

[a] Proposed; no specification issued yet.

trical and thermal conductivities are about the lowest of the copper alloys. The electrical conductivity is about 6.5% of copper and the thermal conductivity 8.4%.

GCuSi welding rods may be used for oxy-acetylene, inert-gas metal-arc and carbon-arc welding. When welding copper-silicon alloys, preheating should be avoided since the low thermal conductivity of the metal makes it unnecessary and the slow cooling of the weld on preheated plates increases the probability of cracking in this hot-short metal. Plates $^3/_{16}$-in. thick and over should be beveled to 45 deg.; plates over $^3/_8$-in. thick should be beveled from both sides.

A slightly excess oxygen flame is used in oxy-acetylene welding to insure against gassing of the weld metal. The welding rods should be free from oxides or grease. Cleaning the rods with steel wool is helpful if they have been in open storage for some time. The rods are painted with a water-paste of a high boric acid flux, or dipped in the dry flux as the welding progresses. As in welding all hot-short metals, the weld should be started 5 or 6 in. from the end of the joint and continued to the short end before proceeding to weld to the other end. This provides cold metal at the starting end to resist the shrinkage stresses in a long joint.

Inert-gas metal-arc welding is being recognized as the best way to weld with GCuSi welding rods on copper-silicon alloys and on copper. Clean welding rods are essential, but no flux is necessary. Direct current, straight polarity is used. The technique for inert-gas metal-arc welding is similar to that for oxy-acetylene welding.

GCuSi welding rods have long been used as filler metal for carbon-arc welding copper-silicon alloys and copper. The carbon electrode is used only with d.c., straight polarity. The joint is prepared as for oxy-acetylene welding. A dry flux of 9 parts fused-borax and 1 part sodium fluoride may be sprinkled along the joint, or the dry flux may be mixed in alcohol and painted on the joint; the flux should not be mixed with water. The arc should be directed at the weld metal, and never at the base metal.

Phosphor Bronze A (GCuSn-A)

Phosphor Bronze A is an alloy of 4 to 6% tin, 0.03% max. phosphorus and the balance copper. The relatively high phosphorus is present to supply an adequate deoxidizing agent for the high temperatures involved when carbon-arc welding. Welding rods of this alloy are used for carbon-arc welding copper where a copper-tin alloy weld metal is not objectionable. They are used on phosphor-bronze plates, on copper-tin-zinc castings and for overlays on steel for bearing or corrosion resisting surfaces.

GCuSn-A welding rods are used generally for carbon-arc welding. The high phosphorus forms an excessive film on top of the molten metal when other welding processes are used. A long arc is used when carbon-arc welding with this alloy, $^3/_4$-in. long for 150 amp. and 1-in. long for 350 amperes. A short arc creates a reducing atmosphere over the molten metal causing porosity; a long arc develops a neutral atmosphere and these gases are not absorbed by the molten metal. The arc should be directed at the weld metal and enough current used to weld at least 10 in. per minute.

Phosphor Bronze D (GCuSn-D)

Phosphor Bronze D is an alloy of 10.5% tin, 0.03% max. phosphorus and the balance copper. The higher tin in this phosphor bronze gives it slightly higher strength and hardness than Phosphor Bronze A. It is used for about the same purposes as Phosphor Bronze A and has similar welding properties. The fact that its melting point is 90°F. lower than GCuSn-A welding rod is a big help in welding copper with the carbon arc.

Copper-Nickel (GCuNi)

Copper-nickel welding rods are used almost exclusively for welding copper-nickel sheet or plate. They are an alloy of approximately 70% copper and 30% nickel. The low thermal conductivity of this metal makes it easy to weld. Since it is hot-short, the usual precautions must be taken.

GCuNi welding rods are used only for oxy-acetylene and inert-gas metal-arc welding with techniques about the same as for GCuSi welding rods. For oxy-acetylene welding, a flux designed for gas welding nickel alloys should be used; no flux is required for inert-gas metal-arc welding.

Naval Bronze (GCuZn-A)

Naval bronze welding rod is nominally

a 60–40 brass (copper-zinc alloy) with less than 1% tin added to improve its strength and corrosion resistance. Its electrical conductivity is about 25% that of electrolytic copper, and its thermal conductivity about 30% that of copper. Its corrosion resistance is about equal to that of the yellow brasses of this type.

GCuZn-A welding rods are used for oxy-acetylene welding. Their high zinc content makes them difficult to use for carbon-arc and inert-gas metal-arc welding. The most common application for these rods is in braze welding steel, cast iron and malleable iron parts. They are also used for gas welding brass and for braze welding copper, bronze, and nickel alloys.

On steel, mill-scale and rust should be removed from the weld zone before welding; the graphite-smear on a ground or smoothly machined surface should be removed from cast iron. The graphite-smear prevents bonding of the bronze with the cast iron and it can be removed by chipping, rough machining or burning off with an excess-oxygen, oxy-acetylene flame. Grease and dirt will cause a poor bond and porosity when braze welding on any metal.

When braze welding with naval bronze and an oxy-acetylene torch, a neutral or slightly oxidizing flame is used with a borax and boric-acid flux which may be applied to the rod or sprinkled on the work. Before depositing weld metal, the weld area is heated to a cherry red. A few drops of bronze-welding rod are melted on the work and heating continued until the bronze flows or tins the base metal. If the groove is not over $^3/_8$-in. deep, it can be filled in one pass. When applying a second pass of bronze, care must be taken not to remelt all of the first layer; fusion of the surface of the first layer with the second layer is all that is necessary. A general preheat of 600 to 1000°F. may be required when braze welding complicated sections of cast iron.

Manganese Bronze (GCuZn-B)

Manganese bronze, like naval bronze, is basically a 60–40 brass (copper-zinc alloy) with additions of less than 1% each of manganese, tin and iron, which increase the strength, hardness and corrosion resistance over that of the straight copper-zinc alloys. Its other properties are quite similar to those of naval bronze. In addition to its use for joining steel and cast iron, it is widely used for building up bearings.

GCuZn-B welding rods are used for oxy-acetylene welding, the technique being the same as for GCuZn-A welding rods.

Low Fuming Bronze (GCuZn-C)

GCuZn-C welding rods are generally similar to manganese bronze in composition. They contain about 59% copper, 39% zinc and less than 1% each of manganese, tin and iron. In addition to these other minor metals, they contain a small amount of silicon which is effective in reducing the fuming or oxidizing of the zinc, hence the name, low-fuming bronze. The weld metal has physical properties similar to manganese bronze and is applied in the same way.

Nickel Bronze (GCuZn-D)

Nickel bronze welding rods differ from the others in the GCuZn group in their color. They are silver white and properly belong to the nickel silver group of copper alloys. They contain about 47% copper, 43% zinc, 10% nickel and small amounts of silicon and phosphorus. The silicon content also imparts to these welding rods low-fuming properties. The nickel content of this alloy lowers its electrical and thermal conductivity to about 10% of electrolytic copper.

GCuZn-D welding rods are used for oxy-acetylene welding, with the same technique as the other bronzes in this group except that slightly higher temperatures are required. They are often used on steel and cast iron where the white weld metal is a better color match than the yellow bronzes.

Refer to Chapter 34 for additional information on the welding of copper and copper alloys.

BRAZING FILLER METAL

General

Filler metal used in brazing is commonly known as brazing alloy. By definition a brazing alloy is a nonferrous metal or alloy having a melting point above 800°F. but below that of the metals being joined. As pointed out in Chapter 22, which contains more detailed information

on brazing, the filler metal is always fed into the joint by capillary attraction.*

A suitable brazing alloy must meet the following basic requirements:

1. It should melt and flow freely within the desired temperature range.
2. It should wet and adhere to the surfaces to be joined.
3. It should produce joints of sufficient soundness, strength, toughness and permanence.
4. It should meet any additional requirements and have any special attributes, such as electrical and heat conductivity, color, resistance to chemical attack and suitable fluidity as needed for specific service conditions.
5. It should be available in a convenient form for the brazing process and assembly for which it is to be used.

Solidus and Liquidus, Melting and Flowing

Pure metals and some alloys used as brazing filler metal melt at single temperatures or over short temperature ranges; other alloys melt over wide temperature ranges. Within a wide range the alloy is slushy; part is liquid and part solid; and the liquid part is of a different composition from that of the solid part. The temperature at which melting starts on heating (or at which freezing finishes on cooling) is technically known as the *solidus temperature,* and the temperature at which melting is completed on heating (or at which freezing starts on cooling) is technically known as the *liquidus temperature.*

It has been general practice to describe the melting ranges of brazing alloys by their melting and flow points. The *melting point* is that temperature below which the alloy is substantially solid; the *flow point* is the temperature above which the alloy is liquid and will run or flow. Actually there have been different interpretations of the two terms. In accordance with a decision made by the AMERICAN WELDING SOCIETY's Committee on Brazing, the thermal points used in this chapter are the technical ones: solidus and liquidus.

The width of the melting range and how the alloy melts and freezes within it materially affect the behavior of the filler metal. Some alloys are almost completely liquid, they flow freely and they are regularly used well below their liquidus temperatures. Other alloys are almost completely solid below their liquidus temperatures, only small amounts remaining liquid. They must be used at or above their liquidus temperatures.

The way an alloy melts is important for some brazing processes. Ordinarily a filler metal with a narrow melting range is desired. Such an alloy remains solid until the brazing temperature is reached at which time it melts and quickly flows into the joint. Furthermore, in furnace brazing, where heating is relatively slow, an alloy with a wide melting range is likely to be subject to liquation, part of the alloy melting and flowing, leaving an unmelted part outside the joint. On the other hand where the fit of the parts is loose an alloy with a wide melting range will frequently fill the joints more easily than one with a narrow melting range.

Generally speaking, a brazing alloy will wet and adhere to the surfaces to be joined if one of the component metals of the brazing alloy will alloy, at least superficially, with those surfaces.

Strength

The strength of a brazed joint depends on the following factors:

The strength of the members being joined: Generally speaking the stronger the members joined, the higher the strength of the brazed joint, the limiting value for the strength of the joint being the strength of the material joined.

The thickness of the filler metal layer: In general, the thinner the layer, the stronger the joint.

How well the filler metal adheres to, or coalesces with, the members joined: Ordinarily the filler metal and brazing technique selected are such that actual alloying takes place with the formation of a strong interfacial layer. A weak brittle product at the interface reduces the strength of the brazed joint.

How free the joint is from flux inclusions or voids: Obviously the strongest joints are those in which the bond extends over the entire joint area, uninterrupted by foreign matter of any kind.

The mechanical characteristics of the structure and just how the load is applied to the joint: The strongest joints are those in which the entire joint area is uniformly loaded. If, as in a butt joint

* Even when the filler metal is preplaced over the entire area of the joint surfaces to be bonded, the wetting of the surfaces by the molten alloy is considered to be the result of capillary action.

subjected to bending, one part of the joint carries a greater part of the load, that part will start to fail first and the entire joint will fail due to a progressive tearing action. If a relatively soft rod is brazed into a relatively hard sleeve and a test is made to determine the shear strength of the joint, the rod may start to neck down where it joins the sleeve creating a radial tensile load in addition to the shear load at that point. The result is failure at a lower load than would be obtained if failure occurred by shear alone. The strength obtained frequently depends on the yield strength of one or both members joined.

The strength of the filler metal itself: The strength of the brazing alloy as determined by testing conventional test specimens of the filler metal is of secondary importance. If the materials joined are softer and less strong than the filler metal, failure will occur in the materials joined and not in the joint. If the materials joined are harder and stronger than the filler metal, failure may occur in the joint, but at loads in excess of the strength of the filler metal itself. This is because the hard joint members support the relatively thin filler metal and prevent a change in shape and lateral contraction which normally occur before failure takes place. Thus a copper filler metal having a tensile strength of 30,000 psi. may yield brazed joints having strengths of 100,000 psi. or more in high strength steel.

Types of Alloys

For convenience of consideration, filler metal for capillary brazing is divided into four more or less arbitrary groups.

1. Silver Alloys
2. Copper and Copper Alloys
3. Copper-Phosphorus Alloys
4. Aluminum Alloys

Silver Alloys.—Silver is introduced into brazing alloys in order to lower their melting temperature, to make them tough and ductile and to provide corrosion resistance. The cost of the silver sometimes has an important effect on the composition of the alloy used, but this factor should be considered in relation to the amount of silver brazing alloy used in relation to the shorter brazing times and lower brazing temperatures made possible by their use.*

The simplest silver brazing alloys are the binary silver-copper alloys. Being free from zinc or cadmium, they have the advantage for some purposes of having low vapor pressures. They oxidize readily when melted and they do not wet some metals as well as alloys containing even small amounts of zinc or tin.

A ternary silver-copper-phosphorus alloy has found wide use in joining copper and copper alloys. It is largely self-fluxing when used on copper. It should not be used on ferrous metals because of the formation of a brittle iron phosphide.

The commonest silver brazing alloys are the ternary alloys of silver, copper and zinc. Some of the compositions now in use originated from the simple expedient of adding silver to the common brasses.

Many silver brazing alloys consist of silver, copper and zinc, with other elements, such as nickel, cadmium and tin added either singly or in combination. Nickel is added to improve wetting on some metals, to increase resistance to corrosion from certain sources and to alter flow characteristics. Cadmium may replace part of the zinc to obtain combinations of low melting and flow temperatures with minimum loss in ductility. Tin is added to lower the melting and flow temperatures and to improve wetting of the binary silver-copper alloys; it also has a whitening effect on the color.

Most silver brazing alloys are malleable and ductile and consequently are available in all the common forms such as: thin sheet, fine wire, strip, rod, finely divided forms, and rings, shims, and washers for preplacement. Some silver brazing alloys such as those used for electrical contacts, are available as integral coatings on fine silver and on certain silver alloys. Such materials are known as *solder flushed stock.*

Standardization on a small number of silver brazing alloys is difficult to achieve for several reasons: an unwillingness on the part of some users to change from compositions that have proved satisfactory; a desire, for cost reasons, not to use a higher silver content than necessary; the proprietary nature of certain compositions.

Table 9 lists the alloys available and contains notes as to their behavior during

* In the arts, high silver alloys are used because they are white and because they do not lower the fineness of the entire article below legal standards.

Table 9—Properties of Silver Brazing Alloys

Silver, %	Copper, %	Zinc, %	Cadmium, %	Solidus, °F.	Liquidus, °F.	Remarks and Notes	
72	28	..	..	1435	1435	White	(1)
15[a, b]	80	..	..	1185	1445[c]	Gray	(2)
5	58	37	..	1545	1610	Yellow	(3)
10	52	38	..	1450	1565	Yellow	(3)
20	45	35	..	1430	1500	Yellow	(3), (4)
30	38	32	..	1370	1410	Yellow	(3)
40	36	24	..	1330	1445	Yellow	(5)
45	30	25	..	1250	1370	Nearly white	(5)
50	34	16	..	1275	1425	Nearly white	(5)
60	25	15	.	1260	1325	White	(6), (7)
65	20	15	..	1280	1325	White	(7)
70	20	10	..	1335	1390	White	(7)
75	22	3	.	1365	1450	White	(7), (8)
80	16	4	..	1360	1490	White	(9)
40[d]	30	28	..	1240	1435	Yellow	(5), (10)
31.5	34	15.5	19	1165	1390	Yellow	(5)
34	27	18	21	1125	1300	Yellow	(5)
35	26	21	18	1125	1295	Yellow	(5)
45[a]	15	16	24	1125	1145	Yellow	(5), (11)
47	20	17.5	15.5	1165	1240	Yellow	(5), (11)
50[a]	15.5	16.5	18	1160	1175	Yellow	(5), (11)
50[a, e]	15.5	15.5	16	1195	1270	Yellow	(10)
56[a, f]	22	17	.	1140	1205	White	(5), (11), (12)

[a] Proprietary alloys.
[b] Also contains 5% phosphorus.
[c] Fluid and regularly used at 1300°F.
[d] Also contains 2% nickel.
[e] Also contains 3% nickel.
[f] Also contains 5% tin.

NOTES:
(1)—Used in vacuum tube manufacture.
(2)—For nonferrous metals only; self fluxing on copper.
(3)—For iron and steel and for nonferrous metals not damaged by temperatures required.
(4)—Temperature low enough for extruded brass.
(5)—For general use on ferrous and nonferrous metals.
(6)—For small parts, work requiring low temperature, high silver; highly corrosion resistant, ductile.
(7)—Silversmiths' solders.
(8)—Fluid at 1425°F.
(9)—Extremely ductile; for joining copper and bronze rods for redrawing.
(10)—For carbides; chloride-corrosion resistant on stainless steel.
(11)—Low-temperature alloys.
(12)—Cadmium-free.

brazing, their uses and any particular characteristics they may have. These alloys are usually available in all the common forms of brazing alloys.

Copper and Copper Alloys.—Electrolytic tough pitch copper is more widely used for brazing than any other type of copper or copper alloy. It is used on steel, usually in furnace brazing with a hydrogen atmosphere. Its melting point is relatively high, 1981°F., but it is relatively inexpensive. It requires no flux in a hydrogen atmosphere and it penetrates the joint area and makes strong, tight, sound joints. The brasses containing about 40% zinc melt and flow at lower temperatures than copper and are malleable and ductile enough to be available in wrought forms; they too make strong, tough joints. The brasses containing about 50% zinc melt and flow at still lower temperatures but, because they are brittle and are not readily rolled or drawn, they are available in lump and grain form only.

Brass filler metal usually requires the use of flux, as zinc will oxidize in any but the driest, oxygen-free atmosphere.

For many years a low-copper, high-zinc, nickel-silver alloy containing 10% nickel has been used for capillary brazing. It is white in color and it makes strong joints at a relatively high temperature (1715°F.).

Table 10 lists the most frequently used copper and copper-alloy filler metals for capillary brazing.

Copper-Phosphorous Alloys.—The copper-phosphorous eutectic, containing 91.7% copper and 8.3% phosphorous, melts at 1305°F. While the alloy of

Table 10—Properties of Copper and Copper-Alloy Brazing Filler Metals

Copper, %	Zinc, %	Other Metals, %	Solidus Temperature, °F.	Liquidus Temperature, °F.	Forms Available[a]	Note
99.9 min.	...	.....	1981	1981	1, 2, 3, 4	(1)
99.9 min.	...	0.012 P, max.	1981	1981	1, 2, 3, 4	(1)
99.0 min.	...	0.04 P	1981	1981	1, 2, 3, 4	(1)
98.0	...	2.0 Si	1805	1905	1, 2, 3, 4	(1)
60	40	.....	1650	1660	1, 2, 3, 4	(2)
60	39.25	0.75 Sn	1630	1650	1, 2, 3, 4	(2)
58	39.25	0.75 Sn, 1.0 Fe, 0.5 Mn	1590	1630	3	(2)
52	48	.....	1570	1595	4	(2)
50	50	.....	1585	1610	4	(2)
48	42	10 Ni	1690	1715	3	(3)

[a] Forms available: 1—Strip; 2—Sheet; 3—Wire; 4—Finely divided.

NOTES:

1—For furnace brazing of steel.
2—For brazing steel, copper, high-copper alloys, nickel, nickel alloys and stainless steel.
3—For brazing steel, nickel and nickel alloys.

eutectic composition is brittle, alloys near the eutectic composition can be worked into sheet, rod and wire forms. An alloy having a solidus temperature of 1370°F. and a liquidus temperature of 1450°F., containing 7 to 7½% phosphorus is available in the form of rod, 1/16 to 1/4-in. diam. wire and rings made from wire. Other alloys of the same type contain 7% phosphorus and either 2% silver or 0.5% tin. These alloys are largely self-fluxing when used on copper. They should not be used on ferrous metals because of the formation of a brittle iron phosphide.

Aluminum Alloys.—Filler metals for brazing aluminum and its alloys are themselves aluminum alloys of suitable compositions so that their melting points are lower than the melting points of the base metal. This lowering of the melting points is accomplished by alloying aluminum with varying amounts of silicon or with copper and silicon. The composition and thermal points of the filler metals are given in Chapter 32.

The alloys are available in the form of wire 3/32, 1/8, 5/32 and 3/16 in. in diam. and, in the case of the aluminum-copper-silicon alloy, in the form of flat wire strip 0.020 x 2 inches.

Filler metal of the aluminum-silicon type is also applied as an integral coating on certain sheet aluminum alloys. This material, known as brazing sheet, is made with one or both sides coated, depending on the requirements of the job.

Fluxes

Proper fluxes are important adjuncts to brazing alloys. What flux to be used, if any, depends not only on the brazing alloy but also on the metals joined. See Chapter 22 for a general discussion, Chapter 32 for fluxes for aluminum and Chapter 34 for fluxes for copper alloys.

SURFACING FILLER METAL

General

A combination of factors including hardness, abrasion resistance, corrosion and impact resistance are to be considered in the selection of filler metal for surfacing applications. The hardness requirements may be in the cold state or over the hot or *red hardness* range. Abrasion resistance requires a degree of toughness permitting minimum wear and is frequently related to hardness. Corrosion resistance necessitates a reduction in susceptibility to chemical attack on exposure to an extensive range of compounds, pressures and temperatures. Impact resistance is the ability to withstand battering loads with a minimum of upset. Thus it is quite different from notched impact resistance of structural members where deformation under load is preferred to brittle failure. All these factors are interrelated leading to composite requirements such as toughness, resistance to wear, erosion, pitting, frictional braking, galling and seizure.

Although most surfacing is performed with the harder metallic compounds, there are important soft surfacing operations employing overlays of bronzes and related

materials for the creation of bearing surfaces and similar applications.

Classification of Surfacing Materials

The magnitude and variety of the surfacing field has contributed materially to the complexity of the available products. In no welding field is selection of the proper electrode more difficult. There is no universally acceptable facing material just as there is no universally applicable wear test. The results of field observation are frequently the deciding factor in evaluating surfacing requirements and defining a satisfactory surfacing material. Previous classifications have relied upon broad groupings highly general in nature; upon deposit hardness, upon structural categories and upon service conditions. As it is possible to produce a given metallurgical structure with several different compositions and to produce several structures with different heat treatments of the same composition, structural classification is technically difficult and unsatisfactory. Methods based on deposit hardness cover but one attribute of surfacing deposits. Use of service conditions requires individual listing of each application resulting in a cumbersome system too unwieldy to be readily grasped. It has been concluded that classification based upon composition of the deposit undiluted by base metal supplies the most useful starting point. Accordingly, the deposit compositions of over 250 commercially available surfacing electrodes as well as many more low-alloy types have been collected and tabulated into major groupings by Subcommittee VII—Surfacing Materials, AWS-ASTM Committee on Filler Metal but in more detail than previously classified. In this manner, several hundred analyses were considered in classifying the commercially available material. The result is tabulated in Table 11. A basic distinction between ferrous and nonferrous alloys is made. The bounding limits of composition are suggested in each case as a guide in identifying the types of material. Absence of limits for given elements in a specific group does not imply that such elements are not present.

The first groupings under ferrous alloys cover carbon steel, low-, medium-, and high-alloy steels at various carbon levels, and high-speed steels. These are all hardenable by heat treatment and going down through the group gives, in general, progressively greater hardness, corrosion and impact resistance and higher abrasion—up to the maximum obtainable with ferrous materials. All but the highest levels of hardness and impact resistance can be obtained with the alloyed members of these groups while abrasion and corrosion resistance are appreciably below levels which can be obtained by other compositions.

The ferrous alloys are completed by the chromium, chromium-nickel, manganese and high-alloy steels. These provide principally austenitic deposits, hardenable by cold work and are not usually heat treated. Certain of the straight chromium steels in this group are ferritic in structure rather than austenitic. All groups discussed thus far require increasing amounts of preheat with increasing alloy content except for the low-carbon chromium-nickel steels. Another exception is the manganese steels which provide a relatively soft deposit which hardens rapidly on cold work to give the best resistance to the impact of battering loads of any compositions listed. Heat treatment and quenching are to be avoided with manganese steel deposits while hot peening is recommended to develop hardness and resist crack formation in the deposit. These groups provide fair hardness with good abrasion and impact resistance extending into more elevated temperature ranges. The manganese steels have found valuable uses on the wearing surfaces of dipper bucket teeth, roll and ring mills, swing hammers, dredge buckets and similar applications. The chromium and chromium-nickel compositions possess corrosion-resistant attributes.

Review of the ferrous alloys suggests the importance of chromium which in increasing amounts and as a function of increasing amounts of carbon available forms the hard, wear-resistant chromium carbide in the deposit. Material of this type has far better service life than carbon steels heat-treated to the same hardness level.

Of the nonferrous alloys the high-alloy group based on chromium, cobalt and tungsten, displays greatest corrosion resistance with good abrasion and impact resistance. Hardness is below that of the highly alloyed ferrous groups and carbide inserts.

The carbides, while brittle, provide

maximum hardness with excellent impact (resistance to upset) and corrosion resistance. Suitably backed up with steel, carbides have excellent resistance to fracture. In homogeneous carbide deposits a continuous alloy of carbides, particularly tungsten carbide, is provided which affords maximum cold and red hardness.

The copper base alloys consist of copper and the bronzes including phosphor, aluminum and silicon bronze. The group is primarily intended for soft-surfacing operations, such as the creation of bearing surfaces and related applications. Phosphor bronze gives a soft deposit of approximately 70 Brinell. A series of aluminum

Table 11—Chemical Analyses of Deposited Metal from Surfacing Filler Metal

	C, %	Cr, %	Ni, %	Total Other Elements, %
		Ferrous Alloys		
Low carbon (see section on low-carbon steel filler metal)[a]	0.19 max	.....	.....	.....
Medium carbon[a]	0.20–0.60	.....	.....	1.0 max.
High carbon[a]	0.61 min.	....	.....	.....
Low alloy-low carbon (see section on low-alloy filler metal)[a]	0.19 max.	.....	...	0.4–6.0
Medium carbon[a]	0.21–0.60	..	....	0.4–6.0
High carbon[a]	0.61–1.50	.....	....	0.4–6.0
Medium alloy				
Medium carbon[a]	0.21–0.60	4–10	....	6–12 incl. Cr
High carbon[a]	0.61–1.70	4–10	.....	6–12 incl. Cr
Medium high alloy				
Low carbon[a]	0.20 max.	10–14	.....	12–30 incl. Cr
Medium carbon[a]	0.21–0.50	10–14	.....	12–30 incl. Cr
High carbon[a]	0.51–2.5	10–14	.....	12–30 incl. Cr
High-speed steel[a]	0.61 min.	0.60–1.20	...	.. ..
Chromium and chromium-nickel low carbon (see section on corrosion-resisting chromium and chromium-nickel steel filler metal)[b]	0.20–1.70	4.0 min.	.	4.0 max.
Chromium-high carbon[b]	0.20–1.70	15.0 min.	7.0 min.	4.0 max.
Chromium-nickel-high carbon[b]	0.70 min		3.5 min.	1.0 Mo, min.; 12.0 Mn, min.[c]
Manganese (Hadfield)[b]	0.60 min	.....	3.5 min.	1.0 Mo, min.; 11.0 Mn, min.[c]
High alloy-high carbon[d]	1.70 min.	4–10	.....	6–12 incl. Cr
	2.51 min.	10–14	....	12–30 incl. Cr
	2.0 min.	22.0 min.	...	30.0 max., incl. Cr
		Nonferrous Alloys		
High alloy (50% min. alloy) Carbides[e]	.	24.0 min.	.	40.0 Co, min.; 3.5 W, min.
Homogeneous deposit	1.8 min.	. . .	....	45.0 min., incl. 5.0 W, min.
Heterogeneous deposit	1.8 min	.	. . .	50.0 min., incl. 45.0 W, min.
Copper base alloys				
Phosphor bronze		.	....	92.0 Cu, min.; 0.10–0.45 P
Aluminum Bronze	.		0.50 max.	80.0 Cu, min.; 8.0 Al, min.
Silicon Bronze	.		.....	85.0 Cu, min.; 5.0 Si, max.
Nickel alloys (see section on nickel and nickel-alloy filler metal)				
Nickel-Copper	.	.	2.0–30.0	70.0–98.0 Cu
Nickel-Pure	...	...	96.0–98.0	6.0 Fe, max.
Nickel-Cr-W-Mo	..	18.0 max.	50.0 min.	6.0 W, max.; 32.0 Mo, max.
Nickel-Cr-B-Si	. .	11.0 max.	80.0 min.	10.5 Si, max.; 2.5 B, max.

[a] Hardenable by heat treatment.
[b] Hardenable by cold work, majority austenitic.
[c] Ni or Mo may be added or both may be omitted.
[d] Not usually heat treated.
[e] Discrete carbide particles in deposit.

Heterogeneous carbide deposits contain discrete particles of the extremely hard carbides set in a softer matrix of alloy steel. The particles are obtainable in tubes which become the electrode or welding rod or may be sprinkled over the area to be surfaced and the binder metal added by welding. Placing of heterogeneous carbide deposits is also known as *hard-setting*.

bronze electrodes is available to give deposits of hardnesses from 115 to over 300 Brinell. Silicon-bronze alloys are obtainable over similar hardness ranges. They can be further softened by heat treatment.

The nickel alloys available include pure nickel, cupro-nickel and alloys with chromium, molybdenum and tungsten or with chromium, silicon and boron. These have

excellent heat- and corrosion-resistant properties in specific uses with fair abrasion and impact resistance.

Selection of Surfacing Materials

In general, the attack on the part will involve one or more of the following: Sliding or rolling friction, shock and impact, heat, erosion and corrosion. Other factors such as smoothness of the deposit desired or the ability of the surfaced part to form an efficient tool also affect the choice. Previous discussions of each classification indicate the relative merits of various groups. For specific applications these must be evaluated on the basis of field experience before selection of the optimum material can be claimed. Cost is not a primary consideration when gaining experience in a new application. After adequate experience is gained, variations can be made to reduce the cost factor. Usually the material giving the longer life is preferable even though the filler metal cost may be higher. The greater service life will more than justify the greater first cost. On the other hand, some experimentation on an established resurfacing operation frequently will reveal a material which gives equal service at a fraction of the cost.

For more specific information on the selection and use of surfacing alloys, refer to Chapter 21.

BIBLIOGRAPHY

1. *Coatings and Fluxes in the Welding of Steel, A Review of the Literature to January 1, 1938,* W. Spraragen and G. E. Claussen, The Welding Journal Res. Suppl., May 1939.
2. *Specifications for Aluminum and Aluminum-Alloy Metal-Arc Welding Electrodes,* American Welding Society and American Society for Testing Materials, 1943.
3. *The Common Mechanical Properties of Carbon Steel Weld Metal in Electric Arc Welding,* O. T. Barnett, The Welding Journal, February 1943.
4. *The Functions of a Welding Flux,* H. H. Griffith, The Welding Journal, June 1943.
5. *Researches for Improved Solder Fluxes,* H. Peters and Bruce Gonser, The Welding Journal Res. Suppl., August 1943.
6. *The Application, Manufacture, Composition and Storage of Coated Metallic Arc Electrodes,* O. T. Barnett, The Welding Journal, April 1944.
7. *How to Select Electrodes for High Quality Vertical and Overhead Work (E6010 and E6011 vs. E6012 and E6013),* H. O. Westendarp, The Welding Journal, June 1944.
8. *Metallic Arc Welding Electrodes,* Harold Lawrence, The Welding Journal: Classifications E6010, E6011 and E6012, July 1944; Classifications E6013, E6020, E6030, E7010 and E7020, August 1944; Stainless Steel, Hard Surfacing and Cast Iron, November 1944; Nickel and Nickel Alloys, Copper and Copper Alloys and Aluminum, December 1944. Also available complete in booklet form from the Penton Publishing Co.
9. *Effect of Phosphorus on the Properties and Welding Characteristics of Arsenical and Non-Arsenical Copper and on Copper Silver Alloy Filler Rod,* M. Cook and E. Davis, The Welding Journal Res. Suppl., October 1945.
10. *Specifications for Iron and Steel Gas Welding Rods,* American Welding Society and American Society for Testing Materials, 1946.
11. *Electrodes for Welding Chromium-Molybdenum Steel,* D. L. Mathias and G. M. Leigh, The Welding Journal, May 1946.
12. *Reduction of Residual Stresses by the Use of Austenitic Electrodes,* E. P. DeGarmo, J. L. Meriam and F. Jonassen, The Welding Journal Res. Suppl., September 1946.
13. *The E601X Electrode Groups,* O. T. Barnett, The Welding Journal, October 1946.
14. *Welding of High Strength Constructional Steel with Ferritic Electrodes,* S. A. Herres and P. E. Woodward, The Welding Journal Res. Suppl., October 1946.
15. *Welding of Hardenable Steels with High Alloy (Austenitic) Electrodes,* S. A. Herres and A. M. Turkalo, The Welding Journal Res. Suppl., October 1946.
16. *Arc Atmospheres and Under-Bead Cracking,* M. W. Mallet and P. J. Rieppel, The Welding Journal Res. Suppl., November 1946.
17. *Development and Applications of Lime Ferritic Electrodes,* D. L. Mathias and A. P. Bunk, The Welding Journal, March 1947.
18. *An Investigation of the Influence of Hydrogen on the Ductility of Arc Welds in Mild Steel,* A. E. Flanigan, The Welding Journal Res. Suppl., April 1947.
19. *Selection of Austenitic Electrodes for Welding Dissimilar Metals,* A. L. Schaeffler, The Welding Journal Res. Suppl., October 1947.
20. *Metal-Arc Transfer as Influenced by Some Materials in the Covering of Welding Electrodes,* C. J. Gayley, The Welding Journal Res. Suppl., November 1947.
21. *Specifications for Mild Steel Arc-Welding Electrodes,* American Welding Society and American Society for Testing Materials, 1948.
22. *Specifications for Corrosion-Resisting Chromium and Chromium-Nickel Steel Welding Electrodes,* American Welding Society and American Society for Testing Materials, 1948.
23. *Specifications for Low-Alloy Steel Arc-Welding Electrodes,* American Welding Society and American Society for Testing Materials, 1948.
24. *Specifications for Copper and Copper-Alloy Metal Arc-Welding Electrodes,* American Welding Society and American Society for Testing Materials, 1948.

CHAPTER 39

DESIGN OF WELDED JOINTS*

INTRODUCTION

Scope

THIS CHAPTER IS chiefly concerned with the design of joints which are to be welded by manual arc and by manual gas welding and brazing.

Joint designs for resistance welding and other processes are not so variable, their selection being greatly affected by electrical and other properties of the base metals, the physical shape of the parts to be joined, the capacity and characteristics of the welding equipment and other special considerations such as accessibility. Therefore, it is considered that any generalizations dealing with joint designs for these processes would be of questionable value to readers of this HANDBOOK. Information on joint designs for these processes, used for specific materials and applications, may be found in recommended welding procedures given in the chapters specifically relating to these subjects.

Importance of Joint Design

Proper joint design is a vital part of a welding procedure for several reasons: proper joint design helps to control distortion, minimizes residual stresses, facilitates good workmanship and results in welds made with the greatest possible economy.

Factors Influencing Joint Design.— The major consideration in joint design is the service for which the product is intended. If the joint is to be subject to corrosion or erosion, care should be taken to provide joints which, when welded, will present few irregularities, crevices or other areas particularly susceptible to such forms of attack. The manner in which stress will be applied in service, whether tension, shear, bending or torsion should be considered. Certain joint designs are suitable only for stress applied in one direction, while others are suitable for use when applications of stress are varied or unpredictable. Similarly, statically and dynamically loaded joints require different designs. Performance of the individual welded joints under different conditions of stress and loading is discussed in a later section of this chapter.

Another factor influencing the design of joints for welding is the efficiency required. The term *joint efficiency* is used to indicate the strength of a welded joint, expressed as a percentage of the strength of the unwelded base metal.

Groove-Welded Joints

Groove welds of different types are used in many combinations for reasons of accessibility, economy and adaptation to the particular design of the structure being fabricated.

The selection of the type of groove weld to use is based largely on economy. The square groove weld is the most economical to use provided satisfactory strength can be obtained, since this weld requires no chamfering. Joint designs for vee and bevel groove welds are for use when materials are so thick that more of the joint must be made accessible for welding in order to obtain sufficient strength. In the interest of economy, joints for vee and bevel groove welds should be selected with root openings and groove angles which will require the smallest amount of weld metal and still

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* Prepared by a committee consisting of C. A. Loomis, Bureau of Ships, Navy Dept., *Chairman*; J. Heuschkel, Westinghouse Electric Corp.; A. N. Kugler, Air Reduction Sales Co.; J. R. McClendon, Bureau of Ships, Navy Dept.; F. G. Outcault, The Linde Air Products Co.; D. W. Puffer, General Electric Co.; A. M. Setapen, Handy and Harman

give sufficient accessibility. J and U groove joints may be used to further minimize weld metal required when the savings are sufficient to justify the more difficult and costly chamfering operations. These joints are particularly useful in the welding of heavy thicknesses. One disadvantage of J and bevel groove joints is the fact that they are difficult to weld soundly due to the one straight side, which makes the entrapment of slag difficult to avoid.

The most important criterion of the strength of a groove weld is the degree of joint penetration. Since welded joints are usually designed so that they will be equal in strength to the base metal, groove-welded joint designs which result in welds extending completely through the members being joined are most commonly used. One of the principles of design is the selection of joint designs which will result in the desired degree of joint penetration. The recommended details of grooves contained herein have been found to provide a degree of joint penetration consistently predictable when the welding is performed within the limits of the prescribed procedure.

Fillet-Welded Joints

Fillet welds are used in preference to groove welds in many cases for reasons of economy where the design permits. Fillet-welded joints are very simple to prepare from the standpoint of edge preparation and fit-up, although groove-welded joints usually require less welding.

When the smallest continuous fillet weld that it is practicable to make results in an efficiency greater than that required, intermittent fillet welding may be used to avoid overwelding, unless continuous welding is required for certain service conditions.

Combined Fillet- and Groove-Welded Joints

Fillet welds are often added to groove welds to improve stress distribution. For this purpose, concave fillets are the more effective. Fillet welds may also be added to groove-welded joints for additional strength.

Brazed Joints

The most important factor in producing a satisfactory brazed joint is the maintenance of a sufficiently thin layer of brazing alloy between the parts joined. Joint clearances must be held to a few thousandths of an inch during the brazing operation to permit the alloy to flow by capillary attraction to all parts of the joint. Clearances too large or too small may prevent proper distribution of the alloy and cause a weak joint. Joints for brazing should also be designed to conserve brazing alloy, and to make uniform heating of the entire joint possible.

The majority of brazed joints are lap joints; however, butt, tee, corner, and edge joints and the *scarf joint,* which is a modification of the butt joint, are also used in brazing.

The brazing alloy may be fed into the joint either manually during heating or preplaced in the joint during assembly. In the former method, used largely for torch brazing, the joint is heated and the brazing alloy is fed into the joint from the outside as the temperature of the joint becomes sufficiently high to cause flow of the brazing alloy. With preplacing, used largely when automatic or semi-automatic heating methods are employed, the alloy melts and is distributed in the joint when the joint has reached the proper temperature. When brazing flat sections wherein shims of brazing alloy strip have been preplaced between the parts, it is good practice to provide means for exerting a slight positive pressure if the parts are small and relatively light in weight. This insures good contact between the parts and facilitates distribution of the proper amount of brazing alloy.

Since most brazed joints are lap joints, the commonest type of loading is shear. Assuming the correct brazing procedure, the following formula can be used to determine length of lap required to give a desired strength:

$$X = \frac{YTW}{L}$$

where

X = Length of lap, in.
T = Tensile strength of the weaker member, psi.
W = Thickness of the weaker member, in.
Y = Factor of safety

L = Shear strength of the brazing alloy, psi.

A more accurate formula for tubing takes into consideration the shear diameter, D.

$$X = \frac{YTW(D - W)}{LD}$$

In selecting joint designs for brazing, economy is an important factor. Since most brazing alloys are relatively costly, the joint design selected should be one which requires a minimum of filler metal. Time required for heating is the other major economic factor; joint designs which will require heating of the smallest mass possible should be used.

RECOMMENDED PROPORTIONS OF GROOVES

The recommended proportions of grooves shown in Figs. 1 to 3 are those which have been found necessary to consistently obtain complete joint penetration when shielded metal-arc welding and gas welding (except pressure gas welding) are used on steel only, since it would be virtually impossible to cover all processes and base metals. Further information on joint design will be found in the chapters covering the various processes.

By giving proper consideration to such factors as base metal melting characteristics, heat effect, heat input, joint penetration obtainable and accessibility it is possible to vary these proportions so as to make them suitable for other materials and processes.

TYPICAL JOINTS WELDED BY MANUAL ARC- AND GAS-WELDING PROCESSES

The following joints include those commonly used with all arc- and gas-welding processes except stud welding and pressure gas welding.

Comments as to joint penetration obtainable apply only to shielded metal-arc welding of steel, since this factor varies with different processes and base metals.

1. SQUARE GROOVE JOINTS, welded from one side, with incomplete joint penetration.

NOTES:
- (*a*) Strength depends on degree of joint penetration, which can be relied upon when adequate procedure control and inspection are employed.
- (*b*) Should not be used when tension due to bending is concentrated at the root of the weld.
- (*c*) Should not be used when subject to fatigue or impact loading.
- (*d*) Most economical from standpoint of preparation and welding required.

2. SQUARE-GROOVE JOINTS, welded from one side, with complete joint penetration.

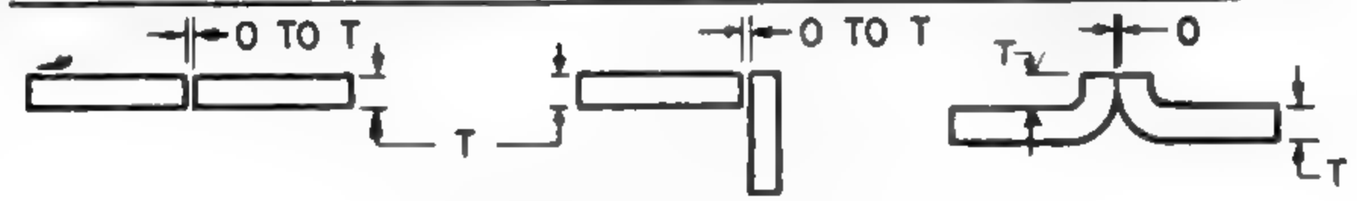
NOTES:
- (*a*) Complete joint penetration obtainable on relatively thin materials.
- (*b*) Fairly strong in static tension, but for full strength, joints 4, 5 and 8 are recommended.
- (*c*) Should not be used when tension due to bending is concentrated at the root of the weld.
- (*d*) Should not be used when subject to fatigue or impact loading.
- (*e*) Economical from standpoint of preparation and welding required.

3. SQUARE GROOVE JOINTS, welded from both sides, with incomplete joint penetration.

NOTES:
- (*a*) Strength depends on degree of joint penetration, plus throat of fillet weld in the case of the corner joint. Careful procedure control necessary for reliable degree of joint penetration.
- (*b*) For static loading only; should not be used when subject to fatigue or impact.
- (*c*) Economical from standpoint of preparation and welding required.

4. SQUARE GROOVE JOINTS, welded from both sides with complete joint penetration.

SQUARE GROOVE JOINTS FOR WELDING ONE SIDE

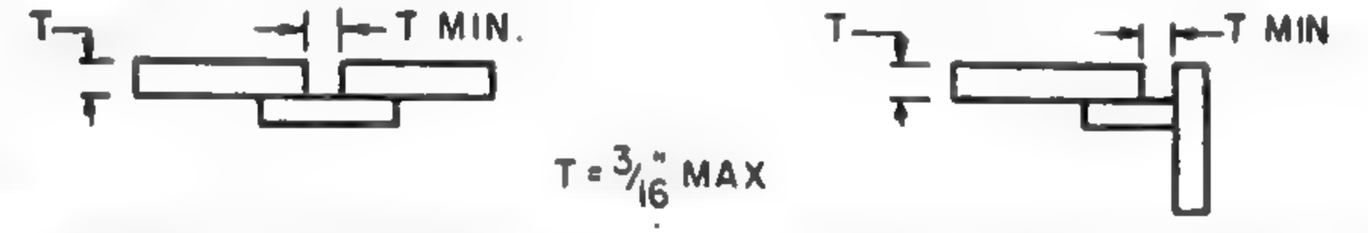


T = 1/16" MAX FOR ALL JOINTS

SQUARE GROOVE JOINTS FOR WELDING BOTH SIDES

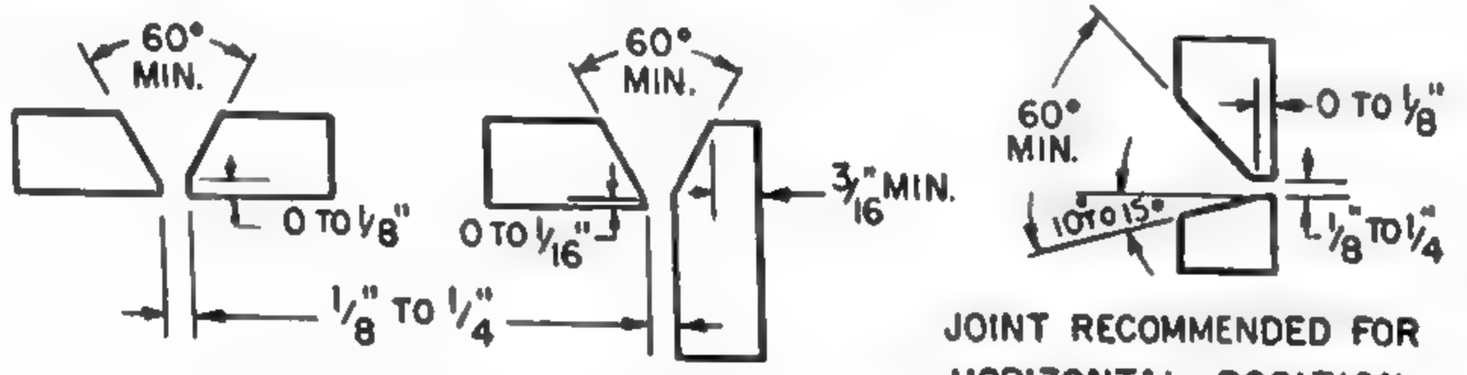
DIM. T	DIM. R
1/8" MAX.	0
1/4" MAX.	T/2

SQUARE GROOVE JOINTS FOR WELDING ONE SIDE WITH BACKING



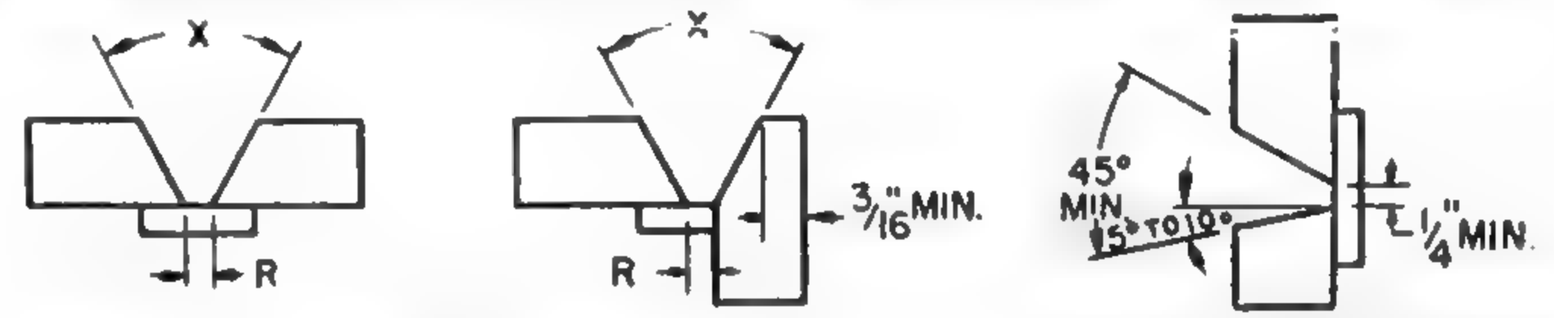
T = 3/16" MAX

SINGLE-VEE-GROOVE JOINTS FOR WELDING ONE OR BOTH SIDES



JOINT RECOMMENDED FOR HORIZONTAL POSITION

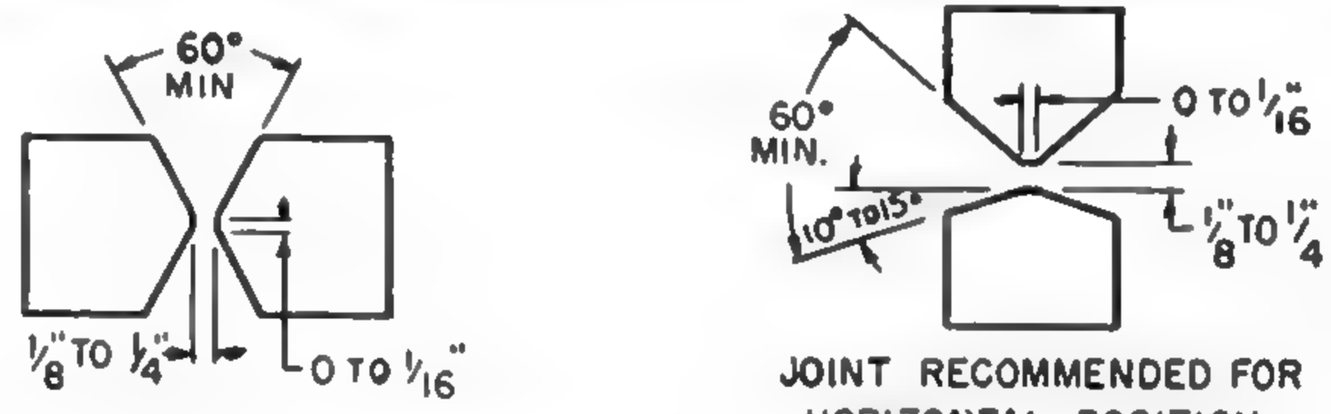
SINGLE-VEE-GROOVE JOINTS FOR WELDING ONE SIDE WITH BACKING



ANGLE X	DIM. R	POSITIONS
45° MIN.	1/4" MIN.	ALL
20° MIN.	1/2" MIN	F, V, O
12° MIN	1/2" MIN.	F

JOINT RECOMMENDED FOR HORIZONTAL POSITION

DOUBLE-VEE-GROOVE JOINTS FOR WELDING BOTH SIDES



JOINT RECOMMENDED FOR HORIZONTAL POSITION

SINGLE-BEVEL-GROOVE JOINTS FOR WELDING ONE OR BOTH SIDES

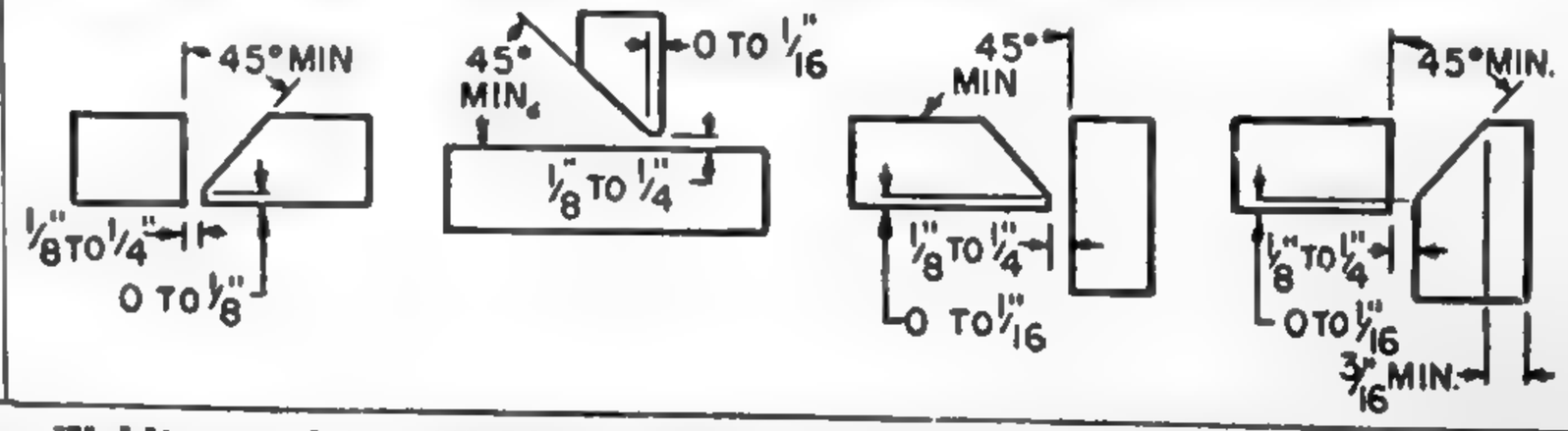
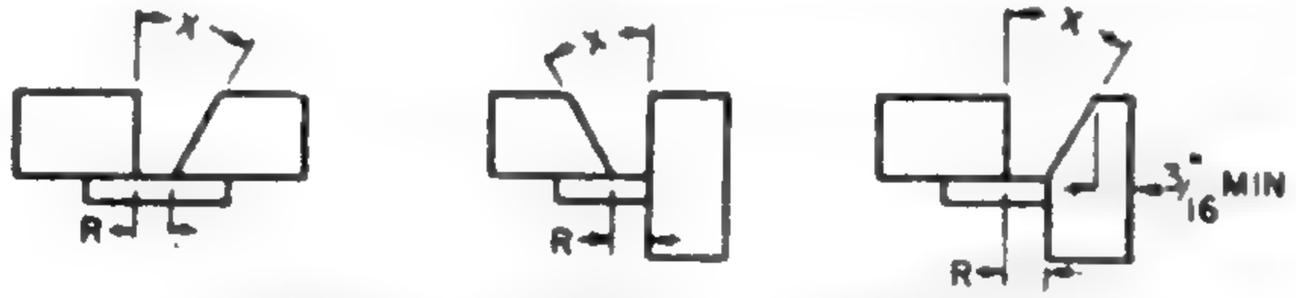


Fig. 1.—Recommended Proportions of Grooves for Metal-Arc Welding and Gas Welding (Except Pressure Gas Welding)

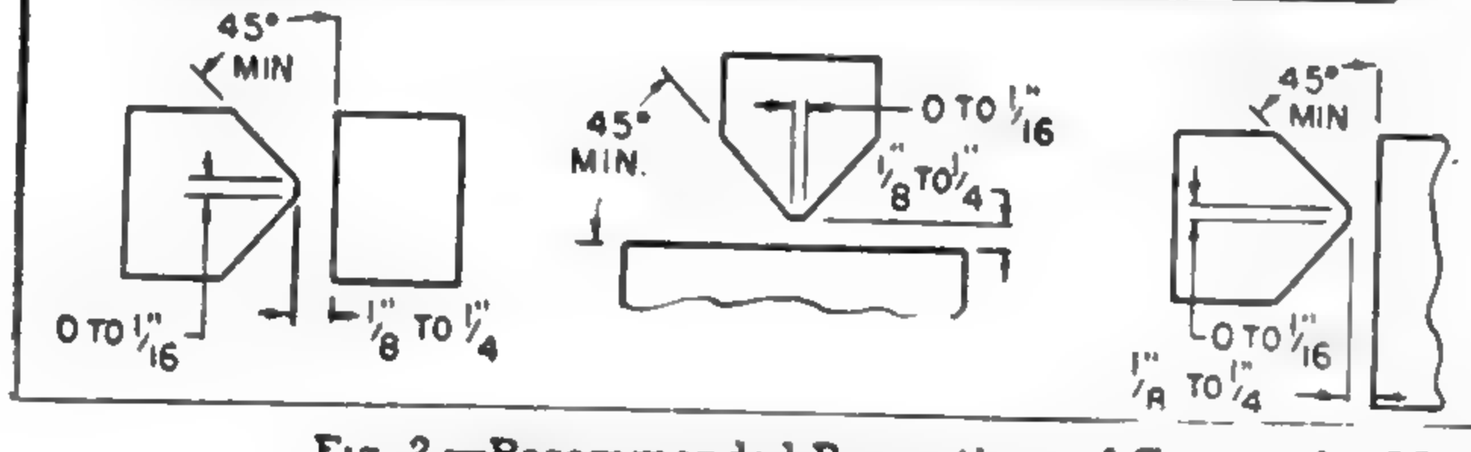
SINGLE-BEVEL-GROOVE JOINTS FOR WELDING ONE SIDE WITH BACKING



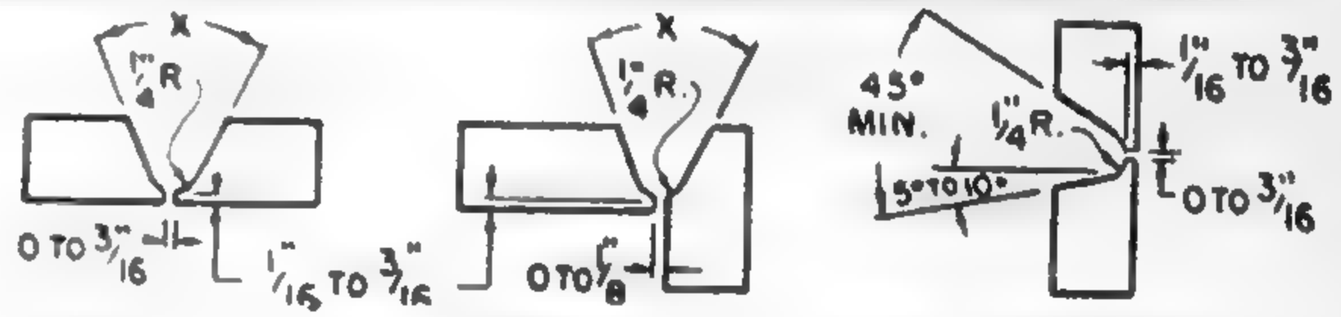
ANGLE X	DIM. R	POSITIONS
45° MIN.	1/4" MIN.	ALL
35° MIN.	3/8" MIN.	ALL
25° MIN.	3/8" MIN	F, V, O

ANGLE X	DIM R	POSITIONS
45° MIN.	1/4" MIN.	ALL
35° MIN.	3/8" MIN.	ALL

DOUBLE-BEVEL-GROOVE JOINTS FOR WELDING BOTH SIDES



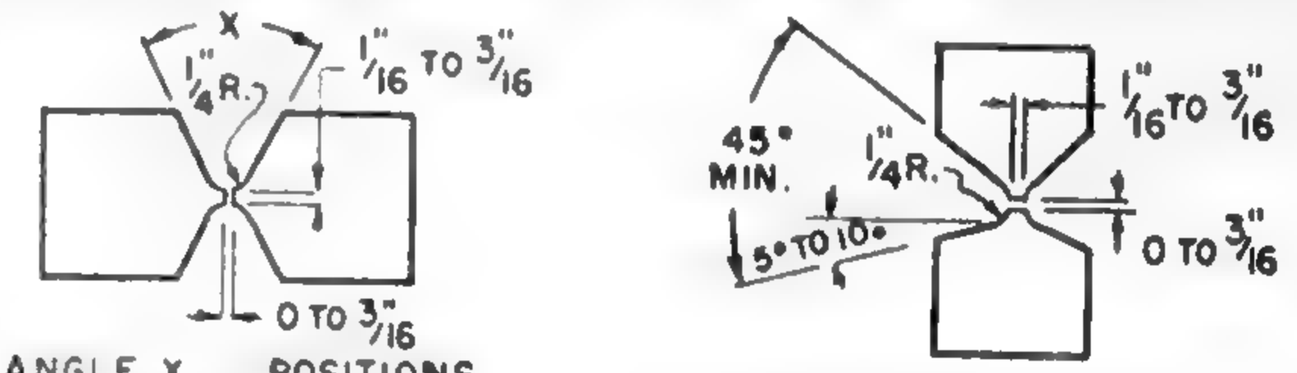
SINGLE-U-GROOVE JOINTS FOR WELDING ONE OR BOTH SIDES



ANGLE X	POSITIONS
45° MIN.	ALL
20° MIN.	F, V, O
12° MIN	F

JOINT RECOMMENDED FOR HORIZONTAL POSITION

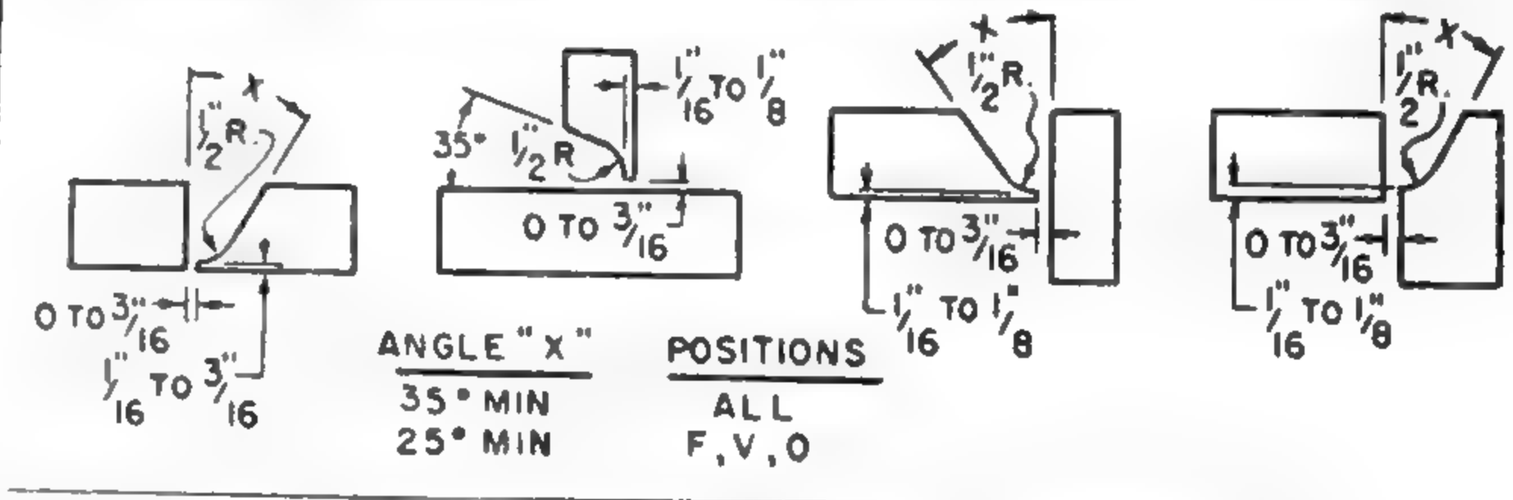
DOUBLE-U-GROOVE JOINTS FOR WELDING BOTH SIDES



ANGLE X	POSITIONS
45° MIN.	ALL
20° MIN.	F, V, O

JOINT RECOMMENDED FOR HORIZONTAL POSITION

SINGLE-J-GROOVE JOINTS FOR WELDING ONE OR BOTH SIDES



ANGLE "X"	POSITIONS
35° MIN	ALL
25° MIN	F, V, O

Fig. 2.—Recommended Proportions of Grooves for Metal-Arc Welding and Gas Welding (Except Pressure Gas Welding)

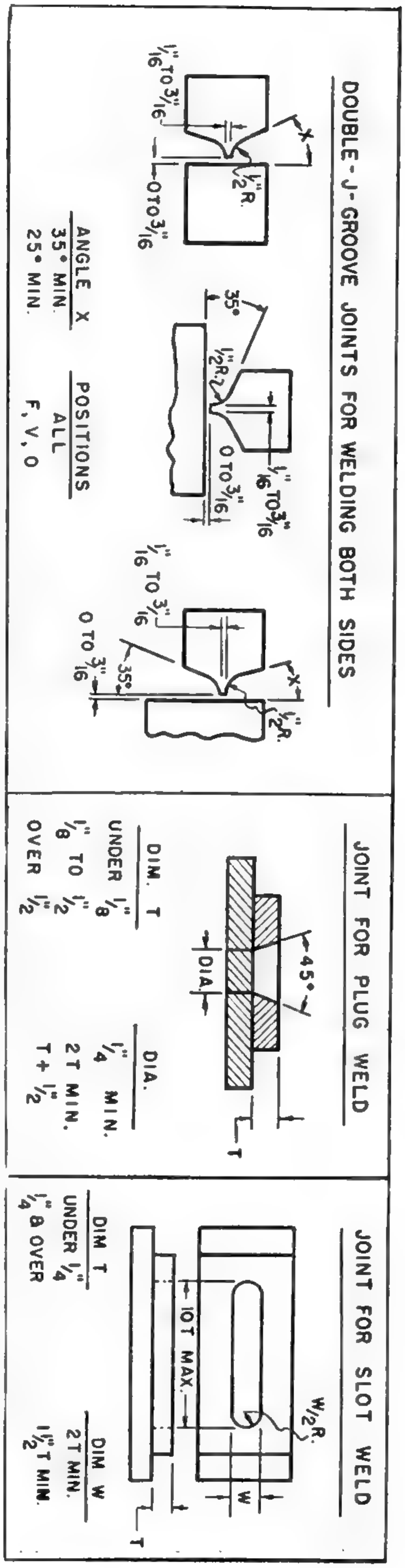


Fig. 3.—Recommended Proportions of Grooves for Metal-Arc Welding and Gas Welding (Except Pressure Gas Welding)

NOTES:

(*a*) Complete joint penetration obtainable with no root opening on materials up to 1/8-in. thick and with adequate root opening (*T*/2), on materials up to 1/4-in. thick.

(*b*) When welding materials 5/16- and 1/4-in. thick, the root of the first weld should be chipped out to sound metal before depositing the second weld, if full strength is desired.

(*c*) Suitable for all types of loading.

(*d*) Economical from standpoint of preparation and welding required.

5. SQUARE GROOVE JOINTS, welded from one side with backing, and with complete joint penetration.

NOTES:

(*a*) Suitable for materials up to 3/16-in. thick with adequate root opening (*T*). For thicker materials, joint 9 is recommended.

(*b*) Useful when all welding must be done from one side.

(*c*) Suitable for all types of loading.

(*d*) Economical from standpoint of preparation.

(*e*) Backing may be removed after welding if desired.

6. SINGLE-VEE GROOVE JOINTS, welded from one side with incomplete joint penetration.

NOTES:

(*a*) Strength depends on degree of joint penetration, which is usually slightly less than the depth of chamfering. For full strength, joint 8, 9 or 11 is recommended.

(*b*) Economical from standpoint of welding required when depth of chamfering does not exceed 3/4 inch.

(*c*) Should not be used when tension is concentrated at the root of the weld.

(*d*) Should not be used when subject to fatigue or impact loading.

(*e*) Economical from standpoint of preparation.

7. SINGLE-VEE GROOVE JOINTS, welded from one side with complete joint penetration.

NOTES:

(*a*) Economical for thicknesses between 1/4 and 2/4 in. from standpoint of welding required.

(*b*) Fairly strong in static loading, but for full strength, joint 8 or 9 is recommended.

(*c*) Should not be used when tension due to bending is concentrated at the root of the weld.

(*d*) Should not be used when subject to fatigue or impact loading.

(*e*) Economical from standpoint of preparation.

8. SINGLE-VEE GROOVE JOINTS, welded from both sides with complete joint penetration.

NOTES:

(*a*) Full strength obtainable for all types of loading.

(*b*) To obtain full strength, the root of the first weld should be chipped out to sound metal before depositing the second weld.

(*c*) Economical for thicknesses up to 3/4 in. from standpoint of welding required.

(*d*) In the case of the corner joint, a fillet weld may be added for additional strength.

9. SINGLE-VEE GROOVE JOINTS, welded from one side with backing and with complete joint penetration.

NOTES:

(*a*) Full strength obtainable for all types of loading.

(*b*) Economical for thicknesses up to 3/4 in. from standpoint of welding required.

(*c*) Desirable when all welding must be done from one side.

(*d*) Backing may be removed after welding if desired.

10. DOUBLE-VEE GROOVE JOINT, welded from both sides with incomplete joint penetration.

NOTES:

(*a*) Strength depends on total joint penetration, which is usually slightly less than the total depth of chamfering.

(*b*) For static loading only; should not be used when subject to fatigue or impact.

(*c*) Economical when depth of chamfering on each side does not exceed 3/4 inch.

(*d*) For full strength, joint 11 or 27 is recommended.

11. DOUBLE-VEE GROOVE JOINT, welded from both sides with complete joint penetration.

NOTES:

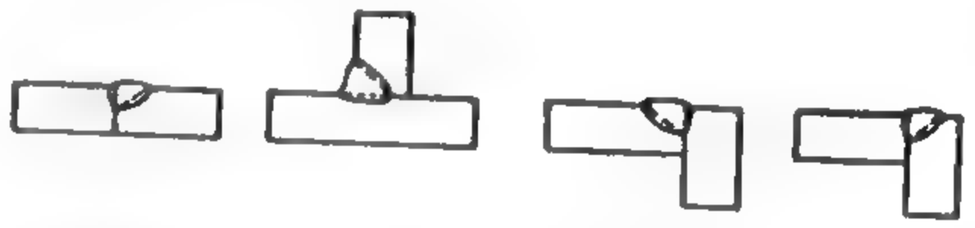
(*a*) Full strength obtainable for all types of loading.

(*b*) Economical for thicknesses up to 1 1/2 in. from standpoint of welding required.

(*c*) To obtain full strength, the root of the first weld should be chipped out to sound metal before depositing the second weld.

(*d*) For thicker materials, joint 27 is recommended.

12. SINGLE-BEVEL GROOVE JOINTS, welded from one side with incomplete point penetration.



NOTES:

(*a*) Strength depends on degree of joint penetration which is usually slightly less than the depth of chamfering.

(*b*) Difficult to obtain a sound weld due to the perpendicular groove face. Vee- and U-grooves preferable.

(*c*) Economical from standpoint of welding required when depth of chamfering does not exceed 3/4 inch.

(*d*) Should not be used when tension due to bending is concentrated at the root of the weld.

(*e*) Should not be used when subject to fatigue or impact loading.

13. SINGLE-BEVEL GROOVE JOINTS, welded from one side with complete joint penetration.

NOTES:

(*a*) Fairly strong in static loading, but for full strength, joint 14 or 15 is recommended.

(*b*) Difficult to obtain a sound weld due to perpendicular groove face.

(*c*) Economical for thicknesses between $^1/_4$ and $^3/_4$ in. from standpoint of welding required.

(*d*) Should not be used when tension due to bending is concentrated at the root of the weld.

(*e*) Should not be used when subject to fatigue or impact loading.

14. SINGLE-BEVEL GROOVE JOINTS, welded from both sides with complete joint penetration.

NOTES:

(*a*) Full strength obtainable for all types of loading.

(*b*) To obtain full strength, the root of the first weld should be chipped out to sound metal before depositing the second weld.

(*c*) Difficult to obtain a sound weld due to perpendicular groove face.

(*d*) Economical for thicknesses up to $^3/_4$ in. from standpoint of welding required.

(*e*) In the case of tee and corner joints, fillet welds may be added for additional strength.

15. SINGLE-BEVEL GROOVE JOINTS, welded from one side with backing and with complete joint penetration.

NOTES:

(*a*) Full strength obtainable for all types of loading.

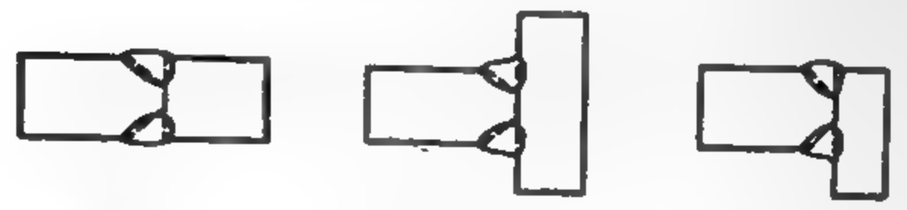
(*b*) Difficult to obtain a sound weld due to perpendicular groove face.

(*c*) Economical for thicknesses up to $^3/_4$ in. from standpoint of welding required.

(*d*) Desirable when all welding must be done from one side.

(*e*) Backing may be removed after welding if desired.

16. DOUBLE-BEVEL GROOVE JOINTS, welded from both sides with incomplete joint penetration.



NOTES:

(*a*) Strength depends on total joint penetration, which is usually slightly less than the depth of chamfering.

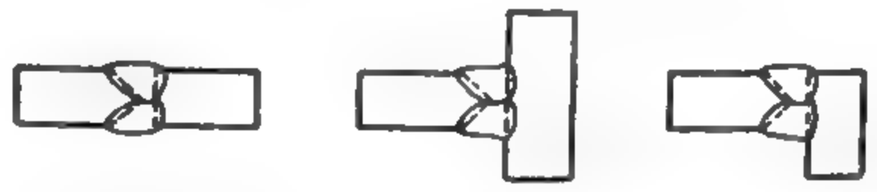
(*b*) Difficult to obtain sound welds due to perpendicular groove face.

(*c*) For static loading only; should not be used when subject to fatigue or impact.

(*d*) Economical from standpoint of welding required when depth of chamfering on each side does not exceed $^3/_4$ inch.

(*e*) For full strength, joint 17 is recommended.

17. DOUBLE-BEVEL GROOVE JOINTS, welded from both sides with complete joint penetration.



NOTES:

(*a*) Full strength obtainable for all types of loading.

(*b*) Difficult to obtain a sound weld due to perpendicular groove face; also difficult to chip the root of the weld.

(*c*) To obtain full strength, the root of the first weld should be chipped to sound metal before depositing the second weld.

(*d*) Economical from standpoint of welding required when thickness does not exceed $1^1/_2$ inch.

(*e*) For thicker materials, joint 22 or 27 is recommended.

18. SINGLE-J GROOVE JOINTS, welded from one side with incomplete joint penetration.

NOTES:

(*a*) Strength depends on degree of joint penetration which is usually equal to or slightly less than the depth of chamfering.

(*b*) Difficult to obtain a sound weld due to perpendicular groove face.

(*c*) More economical from standpoint of welding required when depth of chamfering exceeds $^3/_4$ inch.

(*d*) More expensive to prepare.

(*e*) Should not be used when tension is concentrated at the root of the weld.

(*f*) Should not be used when subject to fatigue or impact loading.

19. SINGLE-J GROOVE JOINTS, welded from one side with complete joint penetration.

NOTES:

(*a*) Fairly strong in static loading, but for full strength, joint 20 is recommended.

(*b*) Difficult to obtain a sound weld due to perpendicular groove face.

(*c*) More economical from standpoint of welding required when thickness exceeds $^3/_4$ inch.

(*d*) More expensive to prepare.

(*e*) Should not be used when tension is concentrated at the root of the weld.

(*f*) Should not be used when subject to fatigue or impact loading.

20. SINGLE-J GROOVE JOINTS, welded from both sides with complete joint penetration.

NOTES:

(*a*) Full strength obtainable for all types of loading.

(*b*) To obtain full strength, the root of the first weld should be chipped out to sound metal before depositing the second weld.

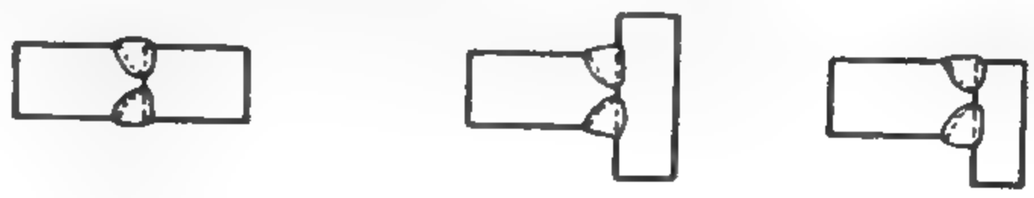
(*c*) Difficult to obtain a sound weld due to the perpendicular groove face.

(*d*) More expensive to prepare.

(*e*) More economical from standpoint of welding required when thickness exceeds $^3/_4$ inch.

(*f*) In the case of tee and corner joints, fillet welds may be added for additional strength and to improve stress distribution.

21. DOUBLE-J GROOVE JOINTS, welded from both sides with incomplete joint penetration.



NOTES:

(*a*) Strength depends on total joint penetration, which will usually be equal to or slightly less than the depth of chamfering.

(*b*) Difficult to obtain a sound weld due to the perpendicular groove face.

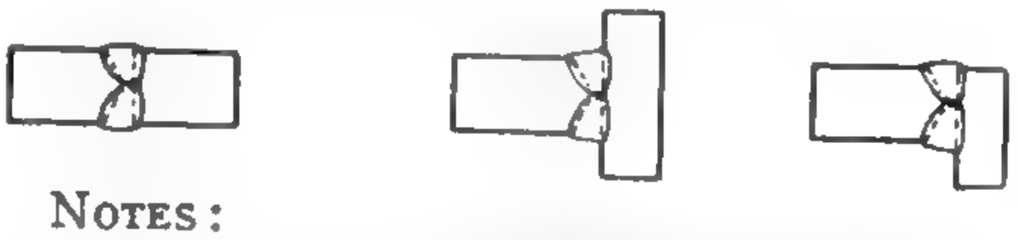
(*c*) More economical when the depth of chamfering on each side exceeds $^3/_4$ inch.

(*d*) More expensive to prepare.

(*e*) For static loading only; should not be used when subject to fatigue or impact.

(*f*) For full strength, joint 22 or 27 is recommended.

22. DOUBLE-J GROOVE JOINTS, welded from both sides with complete joint penetration.



NOTES:

(*a*) Full strength obtainable for all types of loading.

(*b*) Difficult to obtain a sound weld due to perpendicular groove face.

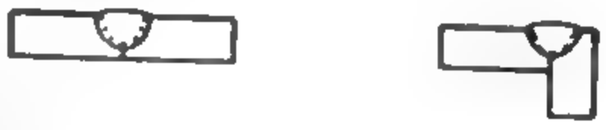
(*c*) To obtain full strength, the root of the first weld should be chipped out to sound metal before depositing second weld.

(*d*) More expensive to prepare.

(*e*) Economical from standpoint of welding required when depth of chamfering on each side exceeds $^3/_4$ inch.

(*f*) In the case of tee and corner joints, fillet welds may be added for additional strength, and to improve stress distribution.

23. SINGLE-U GROOVE JOINTS, welded from one side with incomplete joint penetration.



NOTES:

(*a*) Strength depends on degree of joint penetration, which is usually equal to the depth of chamfering. For full strength, joint 25 or 27 is recommended.

(*b*) Economical from standpoint of welding required when the depth of chamfering exceeds $^3/_4$ inch.

(*c*) Most easily welded groove but expensive to prepare.

(*d*) Should not be used when tension is concentrated at the root of the weld.

(*e*) Should not be used when subject to fatigue or impact loading.

24. SINGLE-U GROOVE JOINTS, welded from one side with complete joint penetration.

NOTES:

(*a*) Fairly strong in static loading, but for full strength, joint 25 is recommended.

(*b*) Economical from standpoint of welding required when thickness exceeds $^3/_4$ inch.

(*c*) Most easily welded groove but expensive to prepare.

(*d*) Should not be used when tension due to bending is concentrated at the root of the weld.

(*e*) Should not be used when subject to fatigue or impact loading.

25. SINGLE-U GROOVE JOINTS, welded from both sides with complete joint penetration.

NOTES:

(*a*) Full strength obtainable for all types of loading.

(*b*) To obtain full strength, the root of the first weld should be chipped out to sound metal before depositing second weld.

(*c*) Economical from standpoint of welding required when thickness exceeds $^3/_4$ inch.

(*d*) Most easily welded groove, but expensive to prepare.

(*e*) In the case of the corner joint, a fillet weld may be added for additional strength.

26. DOUBLE-U GROOVE JOINT, welded from both sides with incomplete joint penetration.

NOTES:

(*a*) Strength depends on total joint penetration, which is usually equal to the depth of chamfering.

(*b*) Most easily welded groove, but expensive to prepare.

(*c*) For static loading only; should not be used if subject to fatigue or impact.

(*d*) Economical from standpoint of welding required when the depth of chamfering on each side exceeds $^3/_4$ inch.

(*e*) For full strength, joint 27 is recommended.

27. DOUBLE-U GROOVE JOINT, welded from both sides with complete joint penetration.

NOTES:

(*a*) Full strength obtainable for all types of loading.

(*b*) To obtain full strength, the root of the first weld should be chipped out to sound metal before depositing the second weld.

(*c*) Most easily welded groove, but expensive to prepare.

(*d*) Economical from standpoint of welding required when thickness exceeds $1^1/_2$ inch.

28. SINGLE-FILLET-WELDED JOINTS.

NOTES:

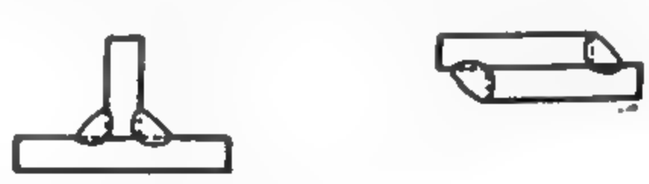
(*a*) Strength depends on size of fillet.

(*b*) No preparation required.

(*c*) Should not be used when tension due to bending is concentrated at the root of the weld.

(*d*) Should not be used when subject to fatigue or impact loading.

29. DOUBLE-FILLET-WELDED JOINTS.



NOTES:

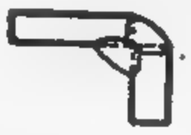
(*a*) Full strength in static loading obtainable with adequate size of fillet welds.

(*b*) No preparation required.

(*c*) Economical from standpoint of welding required on moderate thicknesses.

(*d*) In the case of the lap joint, maximum strength in tension is obtained when the lap equals five times the thickness of the thinner member.

30. DOUBLE-FILLET-WELDED CORNER JOINT, with complete joint penetration.



NOTES:

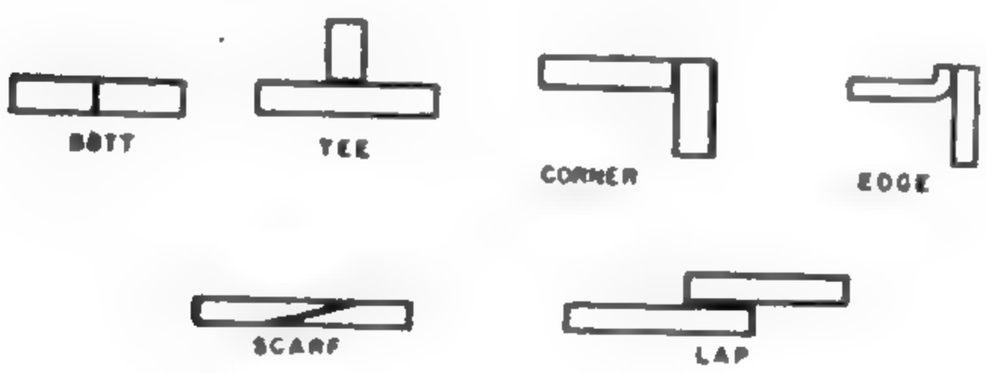
(*a*) Full strength obtainable for all types of loading.

(*b*) To obtain full strength, the root of the first weld should be chipped out to sound metal before depositing the second weld.

(*c*) Economical from the standpoint of welding required on moderate thicknesses.

TYPICAL JOINTS WELDED BY BRAZING PROCESSES

1. FACE-FED AND PREPLACED-FILLER-METAL JOINTS.



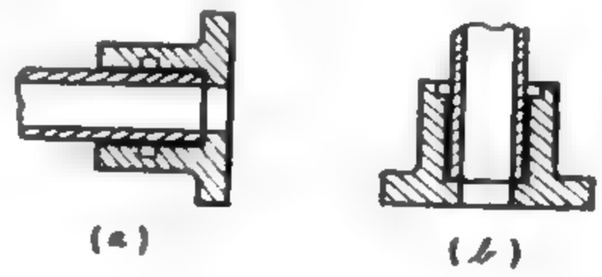
NOTES:

(*a*) In the butt, tee and corner joints shown, the joint clearance is somewhat more difficult to maintain than in the edge, scarf and lap joints.

(*b*) The edge, scarf and lap joints offer a further advantage in that any desired factor of safety can be added simply by increasing the amount of lap.

(*c*) These joints are applicable to both flat and curved members.

2. INSERT-TYPE JOINTS.



NOTES:

(*a*) Inserted ring of brazing alloy maintains clearance until brazing temperature is reached.

(*b*) Joint (*a*) can be brazed in any position; joint (*b*) should be positioned so that the brazing alloy will flow downward.

(*c*) These joints are applicable only to circular or curved members.

CHAPTER 40

PROPERTIES OF WELDED JOINTS*, †

A. IMPACT RESISTANCE

INTRODUCTION

SINCE WELDS like other structural elements often must withstand impact or suddenly applied loads, it is natural that the impact resistance of welds are of interest and that frequent use is made of impact tests for welds. However, for low speeds such as are used in Charpy and Izod tests, the effect of *suddenness* or speed of application is not great. In several European countries, impact tests of welds are required by codes and specifications; as yet such requirements are quite limited in the United States.

TYPES OF TESTS

The principal use of the notch impact test is to determine the transition from ductile to brittle failure with respect to temperature.

Location of Notch

The notch of various specimens has been located in different positions with respect to the center line of the plate or seam. Sometimes it is located at the transition between the base metal and the weld in the heat-affected zone. It is difficult to locate the root of the notch with respect to the fusion and heat-affected zones due to the rapid change in structure at these points.

Correlation with Other Tests

Several attempts have been made to correlate the impact values of welds with the results of tension, bend, hardness, fatigue, X-ray and service tests on identical materials. As in unwelded material, there appears to be no relation between the yield point, tensile strength, energy absorption and hardness and the results of impact tests. There is a general ratio between impact values and elongation but this relationship is by no means exact and sometimes does not apply. Some tests have shown that there is a fair correlation between the energy shown by impact test results and the energy measured by the area under a load-deflection diagram of a similar specimen under static test.

RESULTS OF IMPACT TESTS OF WELDS

General

The following section is a general discussion of results of impact investigations. Only few absolute values have been given since they are generally unimportant except as related to the change in impact resistance in a specific material with changes in temperature. The bibliography at the end of this chapter includes references to the more detailed reports of these investigations.

Low-Alloy Steels

It is impossible to summarize the results of all of the tests made on low-alloy steels. Information on specific alloy steels will be found in Chapter 29, Low-Alloy Steels.

Austenitic Steels

Austenitic filler metal is sometimes used for welding mild steel. Welds made with a mineral-covered electrode containing 25% chromium and 12% nickel in aluminum killed SAE X1020 steel were found

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* Prepared by a committee consisting of A. G. Bissell, Bureau of Ships, U. S. Navy Dept., *Chairman;* L. C. Bibber, Carnegie-Illinois Steel Corp.; G. E. Claussen, Reid-Avery Co.; G. A. Ellinger, National Bureau of Standards, U.S. Dept. of Commerce; F. L. LaQue, The International Nickel Co.; M. A. Scheil, A. O. Smith Corp.

† This chapter covers impact, fatigue and corrosion resistance only. Other properties such as strength and weldability are covered in other chapters of this HANDBOOK relating to specific metals and specific applications.

to have Izod values of 70 ft.-lb. at + 70°F. and 60 ft.-lb. at —184°F. Heat treatment for two hours at 1100°F. with furnace cool or one-half hour at 1560°F. with an air cool had no effect on different grades of austenitic weld metal.

Nonferrous Welds

Oxy-acetylene welds in soft and hard tempers of aluminum (99.5% Al alloy, 0.39 and 0.79-in. thick) welded with aluminum welding rods of commercial purity have been found to have about one-half the notch impact value of unwelded base metal. Cold hammering was found to improve the notch impact value to some extent and hot hammering increased the impact resistance to that of unwelded base metal.

Resistance Welding

Several investigations have been made on the impact resistance of spot and seam welds. Reports of some of these investigations will be found in articles listed in the bibliography at the end of this chapter.

Heat Treatment

Stress-relief heat treatment has been found to restore the ductility in the embrittled zone of manually made arc welds in medium carbon steel (0.20% C, 0.54% Mn) plate. Annealing just above $A_{c}3$ may raise the impact value of such welds by 30%, at 70°F.

Welds at Low Temperatures

Notch impact testing is used often to determine the transition temperature of welds and welded joints. The transition temperature or temperature range has been defined as that temperature or range at which the notch impact specimen shows a change from ductile to brittle behavior. It has been found that in structural steel the toughness of weld metal is very similar to that of the base metal at room temperature and down to —20°F. The transition temperature of a given steel depends upon the velocity of loading during testing and on the degree of stress concentration. Arc welds (0.10% C, 0.6% Ni), made in two and three passes using direct current and stress relieved, were found to have impact values of 36 ft.-lb. at 70°F. and 22 ft.-lb. at —76°F. using a Charpy specimen. These values were the same as for fine-grained. rolled 0.09% carbon steel when tested with the notch perpendicular to the direction of rolling or slightly below those for rolled 0.25% C, 2.4% nickel steel when tested with the notch parallel to the direction of rolling. The heat-affected zone in a low-carbon steel containing 2.33% nickel was found to have the same Charpy impact value (36 ft.-lb.) as unwelded base metal when tested at —76°F.; stress-relief heat treatment of this steel raised the impact resistance of the weld metal only 4 ft.-lb.

Tensile impact tests of machine welds, made by atomic hydrogen welding and flash welding in steel containing 0.25% C, revealed that the welds had about the same ductility as, but 20% lower energy of fracture than, the base metal at all temperatures.

Welds made in 18–8 stainless steel by both gas and arc welding were found to have 50% less energy of fracture than unwelded material of the same composition, but 50% higher than plain carbon steel. Although the energy of fracture was found to be a little higher at —112 than at +70°F., there was no difference in ductility at both temperatures, all fractures being fibrous. Almost no correlation existed between static tension and impact tension results at temperatures ranging from +70 to —112°F. Other tests have shown that there is very little decrease in the tension impact value of 18–8 welds in mild steel down to —112°F.

Welds made in steel containing 0.20% carbon and 3.5% Ni were found to have about the same energy of fracture at —100°F. as at +70°F. On the other hand, with the carbon content increased to 0.35%, the steel when tested at —50°F. had only 10% of the energy of fracture at room temperature. Less pronounced differences were found in welds made in plain carbon steel and 2% nickel steel.

SERVICE OF WELDED STRUCTURES

In general, welded structures of suitable materials wherein the welds are made in accordance with proper procedures, etc., can be expected to have excellent impact resistance in service. By impact resistance in service is meant either the repeated hammer blow received, say, by a welded rail joint from a passing locomotive or a sudden blow of unusual intensity which a weld must absorb to prevent failure and widespread damage.

In welded structures a considerable portion of the energy of impact may be absorbed by the elastic deformation of material adjacent to the weld. Welded beams have been found to have as good drop-impact resistance at 70°F. as unwelded beams, but the welded beams became brittle at —40 and —62°F., at which temperatures the unwelded beams remained ductile. The difference in behavior may have been due to three factors: (1) residual stresses, (2) notches present in the welded beams but not in the unwelded beams and (3) brittle zones in the vicinity of the weld due to low temperature.

B. FATIGUE STRENGTH

NATURE AND SIGNIFICANCE OF FATIGUE FAILURE

Static failure may be due either to permanent distortion or fracture. In either event, it depends, except for very brittle metals, upon the average strength and ductility of a considerable volume of metal. Under static load or load repeated a few times, localized plastic action or even a minute localized fracture (crack) rarely causes appreciable structural damage.

Fatigue is a progressive failure, originating at some localized region where there is a structural weakness or structural damage has occurred. Continued repetition of a sufficiently high load causes a minute crack to develop in that region of localized structural damage, and then to spread, until fracture of the structural part occurs. This means that under repeated loading, minute localized structural damage, which would be negligible under static loading, may be of vital importance.

In the construction of rotating equipment the use of welding requires careful attention to insure that surface irregularities and internal defects are not present to act as stress raisers under fatigue loading. Experimental work has shown that under equivalent fatigue conditions, welds finished flush with the base metal give performances equal to the base metal while those with unfinished surfaces fail after a short period of testing. Where these conditions are met, welding has proved entirely satisfactory as in the construction of internal combustion engines, turbines, propulsion shafting, etc. Careful designing of the members that carry the reversing stresses to avoid sharp changes in section is imperative.

Stress Raisers

The ordinary formulas of mechanics of materials have been developed mainly for the design of structural members subjected to static load, and they almost entirely neglect to consider localized stresses due to non-homogeneity of material and sudden changes of cross-section in structural parts. There are very many localized regions in structural parts where the stress is higher, sometimes much higher, than that computed by the ordinary formulas for strength of materials.

Any cause which produces a localized area of high stress is called a *stress raiser*. Abrupt changes in section, notches, grooves, screw threads, surface irregularities and discontinuities, such as cracks, holes or inclusions, are stress raisers. There is a possibility that an abrupt change in the physical properties of a material, such as may occur at the junction of the weld metal and base metal when the two are of materially different compositions, acts as a stress raiser. The effects of a round hole in a plate and of some other simple stress raisers have been determined by elaborate mathematical analysis and by studies of transparent models viewed by polarized light, but, because the effect of stress raisers on the fatigue strength of a specimen is a function of the physical properties of the material as well as of the geometrical shape of the stress raiser, these studies are of limited usefulness in predicting the value of the fatigue strength of a joint. However, they yield results on the safe side, and are of real value in determining types of geometrical stress raisers to be avoided.

A distinction should be made between the fatigue strength of weld metal and the fatigue strength of welded joints. The former is affected by the properties of the filler and base metals, and by such stress raisers as porosity, slag inclusions and surface imperfections. The latter is affected by all of the above and also by lack of fusion and by geometrical stress raisers incident to the design and fabrication of the joint. The latter are often more injurious than the former. Figure 1 shows a typical double-vee groove weld

in a plate. The abrupt change in section at the edge of the reinforcement constitutes a stress raiser that may overshadow

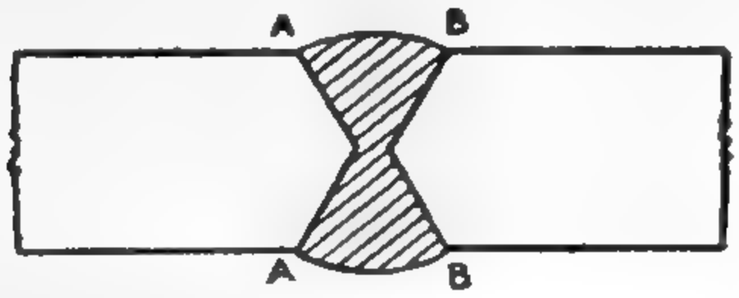

Fig. 1.—High Stress Concentration at Edge of Reinforcement in Double-Vee Groove Weld

the effect of imperfections in the weld. Tests of groove welds in $^{7}/_{8}$-in. plates (0.23% C and 0.47% Mn) showed that the fatigue strength (0 to tension, failure at 2,000,000 cycles) was 22,500 psi. in the as-welded condition, 28,400 psi. when the reinforcement was machined off and 31,600 psi. for an unwelded plate. That is, eliminating the stress raiser due to the change in section at the edge of reinforcement increased the fatigue strength of the joints 25% to a value only 10% less than the fatigue strength of unwelded plate.

The abrupt changes in section at the edges of a transverse fillet weld, shown in Fig. 2, are also severe stress raisers that greatly impair the fatigue strength of the joint.

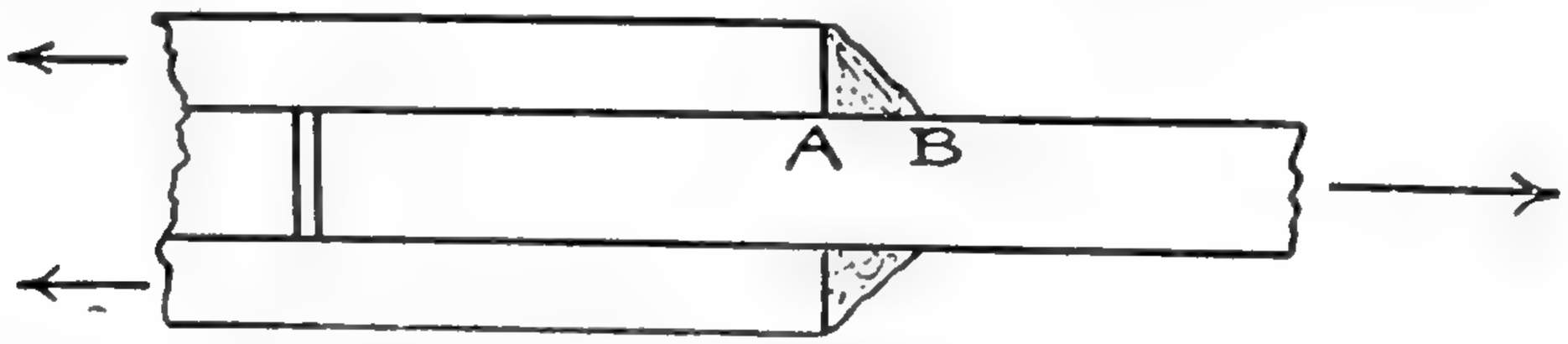

Fig. 2.—Fillet Weld with High Stress Concentration at Toes

The fatigue strength of a joint consisting of plates connected wholly or partly with longitudinal fillet welds, shown in Fig. 3, is low, due to the fact that the stress is introduced into the plate along the edges and piles up at the end of the fillet, tending to cause fatigue failure of the outer plates at locations *A* or of the inner plates at locations *B*. This, being in addition to the stress-raising effect of the change in section, greatly reduces the fatigue strength of the joint. So great is this destructive effect that a joint designed for a longitudinal shear stress of 20,000 psi. at the throat of the weld and a tensile strength of 10,000 psi. on a transverse section of the outside plates, failed in the plates, the weld remaining intact.

The destructive effect of the stress raisers in welded joints that are used to connect structural members is known to be very great and varies with the type of joint.

Definitions and Nomenclature

New developments in the study of fatigue of metals are taking place so frequently that anything like fixed standards of definitions and nomenclature have not been established. The following definitions are given for use in reading this section.

Repeated Stress.—A structural member or a machine part is subjected to repeated stress if, during its regular service, the stress fluctuates because of vibration, change of load, change of temperature or other cause. Repeated stress is a general term and includes pulsating stress and reversed stress, which terms are defined later.

Fatigue of Metals.—When, under the influence of repeated stress, a crack starts and spreads in a structural member or machine part, fatigue of metals is in progress. *Progressive fracture* would be a better term than fatigue of metals.

Pulsating Stress.—A stress varying between a maximum value and a minimum value, both stresses being in the same direction. The minimum value of a pulsating stress cycle may be zero as shown in Table 1 (3) and Table 1 (7), or some numerically larger value as shown in Table 1 (2) and Table 1 (8).

Reversed Stress.—A stress varying between a maximum value in one direction and a minimum value in the opposite direction, such as a cycle of stress in which the stress ranges from tension to compression. The numerical values of the maximum and the minimum stress may be the same, as shown in Table 1 (5), or

different as shown in Table 1 (4) and Table 1 (6). When the maximum and minimum numerical values of stress are the same the terms *alternating stress* and *completely reversed stress* are sometimes used.

Fatigue Limit.—The numerically largest repeated stress which, without causing fracture, may be applied to a given material for an indefinitely large number of cycles. If used without a qualifying adjective, fatigue limit usually means the limit for an indefinitely large number of cycles under completely reversed (alternating) stress. Figure 4 (*a*) shows the type of stress-cycle or *S-N* diagram most commonly found for metals. The diagram approaches a horizontal line as the number of cycles necessary for fracture increases, and the ordinate of this horizontal line is taken as the fatigue limit for an indefinitely large number of cycles of stress. For some metals the *S-N* diagram does not approach a horizontal line. In such a case it is necessary to determine a fatigue strength for a definite number of cycles of stress. Figure 4 (*b*) shows the determination of fatigue strength for 200,000 cycles of stress (FL_B) and for 50,000,000 cycles of stress (FL_C).

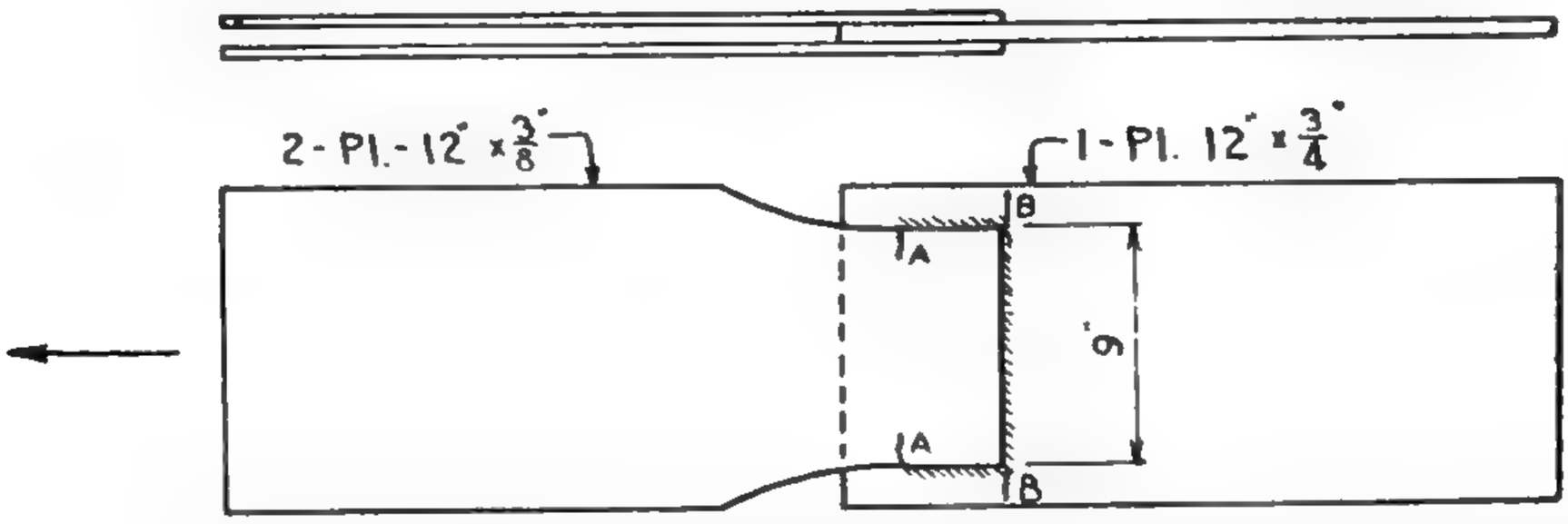

Fig. 3.—Longitudinal Fillet Weld with High Stress Concentration at Ends of Fillet

While no system of quantitative nomenclature has become recognized as standard for repeated stress, two systems are in use in English-speaking countries. In the first system the nomenclature is based on *range ratio*, conveniently denoted by *r*. This is the ratio of the (numerically) smallest stress during a cycle to the (numerically) largest stress; *r* may be either + (no reversal of stress) or — (partial or complete reversal), and is never numerically greater than 1. To define a cycle of stress completely the numerical value of *r* together with the proper sign (+ or —) and the magnitude and kind of the largest stress in the cycle

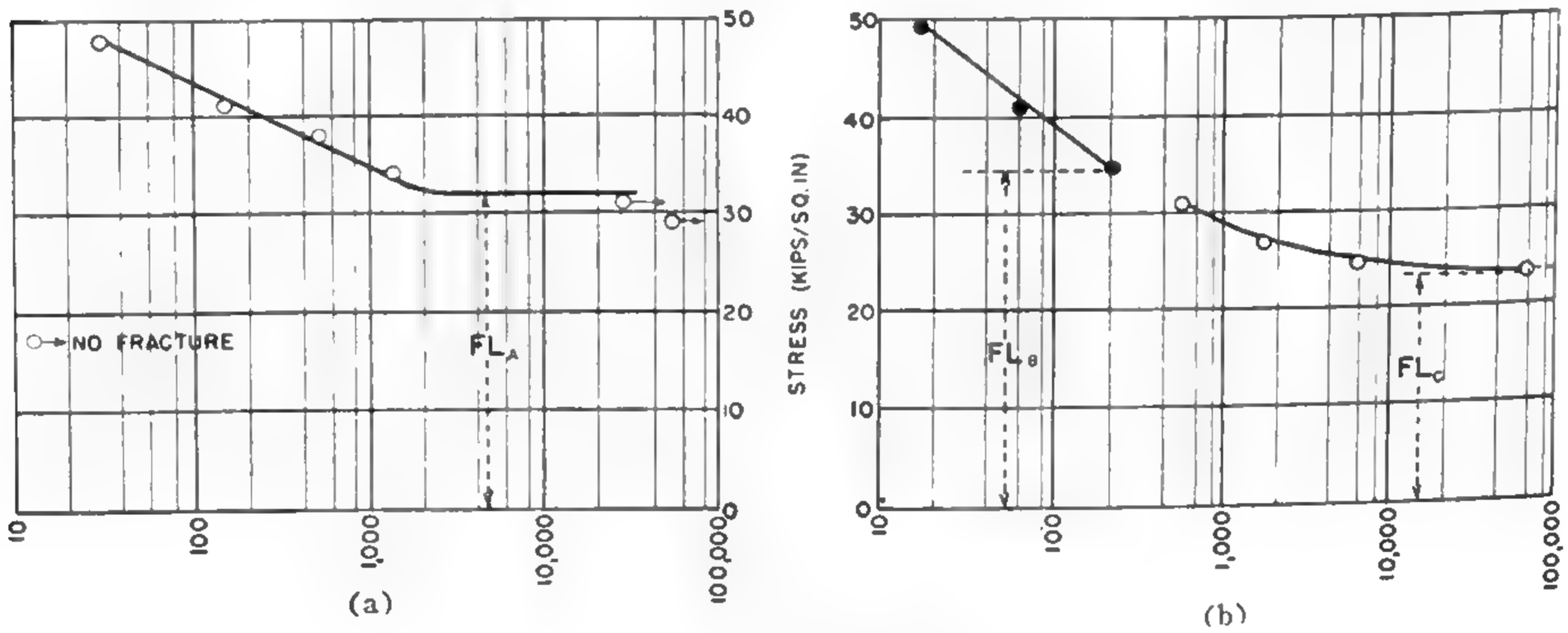

Fig. 4.—S-N (Stress-Cycle) Diagrams for Fatigue Tests

FL_A—Endurance limit 32,000 psi., indefinitely large number of cycles of stress (S-N diagram becomes horizontal).
FL_B—Endurance limit 34,000 psi., 200,000 cycles of stress.
FL_C—Endurance limit 24,000 psi., 50,000,000 cycles of stress.

Table 1—Numerical Examples of *Range Ratio* and *Mean Stress* Nomenclature for Repeated Stress

In this table are given nine typical examples of the use of two systems of nomenclature for cycles of tensile and compressive stress. A similar tabulation could be made for cycles of shearing stress uni-directional and reversed. All values of stress are given in pounds per square inch.

Range of Stress Applied During Cycle	Diagram of Stress During Cycle	Range Ratio Nomenclature: Range Ratio (r)	Range Ratio Nomenclature: Maximum Stress	Mean Stress Nomenclature: Mean (Steady) Stress S_m	Mean Stress Nomenclature: Reversed (Alternating) Stress S_a
(1) Steady stress, 30,000 tension		+1.0	30,000 tens.	30,000 tens.	0
(2) Pulsating stress from 10,000 tens. to 25,000 tens.		+0.4	25,000 tens.	17,500 tens.	±7,500
(3) Pulsating stress from zero to 20,000 tens.		0	20,000 tens.	10,000 tens.	±10,000
(4) Partly reversed stress from 5000 comp. to 18,000 tens.		−0.278	18,000 tens.	6,500 tens.	±11,500
(5) Completely reversed stress from 13,000 tens. to 13,000 comp.		−1.0	13,000 tens. or comp.	0	±13,000
(6) Partly reversed stress from 6000 tens to 22,000 comp.		−0.273	22,000 comp.	8,000 comp.	±14,000
(7) Pulsating stress from zero to 24,000 comp.		0	24,000 comp.	12,000 comp.	±12,000
(8) Pulsating stress from 10,000 comp. to 20,000 comp.		+0.5	20,000 comp.	15,000 comp.	±5,000
(9) Steady stress, 35,000 comp.		+1.0	35,000 comp.	35,000 comp.	0

must be given. Examples of this nomenclature are given in Table 1. This system has proved convenient for machine designers and structural engineers, since for machines and structures being designed the ratio of minimum to maximum load is frequently known.

The second system of nomenclature is based on the fact that any cycle of repeated stress may be regarded as made up of a mean steady stress, S_m, and an alternating (completely reversed) stress, S_a, superimposed on the steady stress. Examples of this nomenclature are given in Table 1. This system is convenient for use in the analysis of test data, and for plotting diagrams to show the effect of varying range of stress on the fatigue strength of a metal.

Efficiency of a Welded Joint.—The efficiency of a welded joint is the ratio of the strength of the welded joint to the strength of the base metal; this definition is similar to that for the efficiency of a riveted joint. The efficiency is expressed in percent. By some writers this ratio, when applied to fatigue test results, is called the *weld endurance ratio.* However, in the United States the term *fatigue ratio* is rather commonly used to denote the ratio between fatigue limit under reversed flexure and static tensile strength.

FATIGUE-TESTING MACHINES AND SPECIMENS FOR WELDED JOINTS

The fatigue strength of a welded joint depends upon the geometrical properties of the specimen as well as upon the physical properties of the material. Moreover, the fatigue failure of a welded joint frequently occurs in the base metal adjacent to the weld rather than in the weld itself. This is not necessarily due to metallurgical injury to the base metal, but may be due to geometrical stress raisers, which, in turn, depend on the details of the joint. For this reason it is necessary, if the fatigue data are to be useful, to test the actual joints or type of construction to be used. While this is often not feasible, actual conditions may either be simulated or approximated for the purpose of fatigue testing.

Specimens tested for determining the fatigue strength of welded joints used for connecting structural members and machine parts should be as large as it is feasible to test and should have the geometrical characteristics and surface finish of the prototype. The specimens used in most tests of this type have been: (1) plates connected with butt welds and subjected to an axial load; (2) channels connected to plates or a plate connected to other plates by either transverse or longitudinal fillet welds, or a combination of the two, subjected to a pulsating or reversed axial load; (3) welded joints connecting beams to columns subjected to a pulsating or reversed moment.

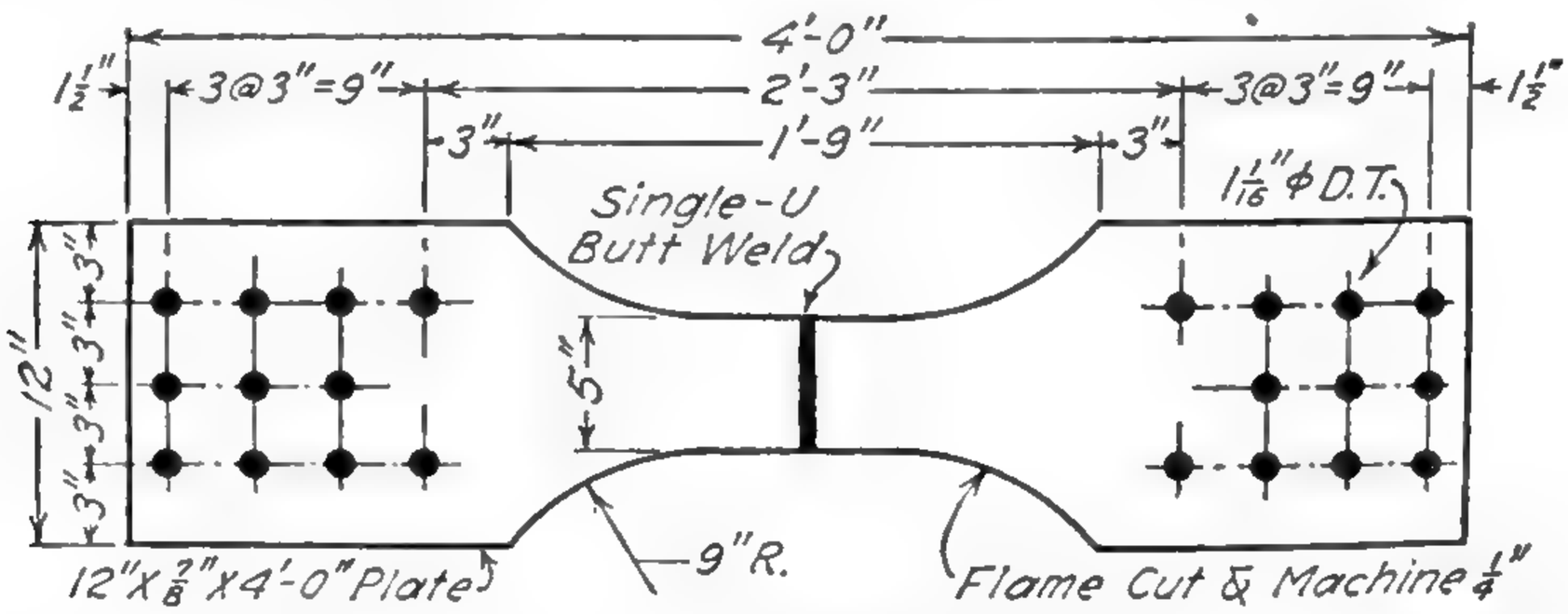

Fig. 5.—Welded Joint Specimen for Testing Under Repeated Axial Stress

Figures 3, 5 and 6 show specimens typical of many that were tested in a comprehensive investigation of the fatigue strength of welded joints sponsored by the Welded Research Council. A lever type of fatigue-testing machine capable of producing a cycle in which the load varied from a tension of 200,000 lb. to a compression of the same magnitude was used for these tests. Moreover, either the maximum or minimum load could be adjusted independently of the other so as to obtain any desired stress cycle so long as neither the tension nor the compression exceeded 200,000 lb.

The characteristic features of this machine are:

1. A lever for multiplying the force.
2. An adjustable-throw crank for moving the outer end of the lever up and down the amount necessary to produce the desired stress in the specimen.
3. Three fulcrums or pivots, one to support the lever, one to connect the short end of the lever to the upper pulling head and the third to connect the lower pulling head to the frame of the machine.
4. Heads for attaching the specimen to the machine.
5. A dynamometer for measuring the force.
6. Power for rotating the crank.

Figure 7 is a schematic drawing of this machine. It consists of the specimen S, the pulling heads H_1 and H_2, the lever L, the crank C, the dynamometer D and the pivots at the ends of the pulling heads and the lever support.

Figure 8 shows a machine that was used to subject a beam-to-column joint to reversed and pulsating moments. It consists essentially of a variable-throw crank, a dynamometer and a mechanical drive. It was used successfully to test connections between 12-in. I-beams and 12-in. steel columns.

Figure 9 shows an arrangement for subjecting boiler drums or other pressure vessels to cycles of repeated hydraulic pressure. Steady pressure is furnished by a hydraulic accumulator, and water under pressure is alternately admitted to and allowed to escape from the vessel under test. This is accomplished by valves operated by a motor-driven series of levers. Such an apparatus has been used with hydraulic pressure as high as 1570 psi. and at a speed of 15 cycles per minute.

Oscillators sometimes are used for the fatigue testing of full-size structural members of complete structures, such as beams, girders and bridges. The oscillator consists of discs rotating on parallel shafts. Each shaft is driven by a motor and the shafts are geared together so as to rotate in opposite directions at the same speed. An eccentric mass is attached to each disc. By placing the eccentric masses at different distances from the center of the disc and by varying the speed of the shafts, the load on the member can be varied. High speeds give increased loads and increased frequency of stress cycles. Oscillators have been used to impose fatigue loading on the decks of vessels and on the floors of railroad bridges.

FATIGUE STRENGTH OF SPECIMENS FROM WELDED JOINTS

Fatigue failure of a welded joint may occur in any one or a combination of several different ways:

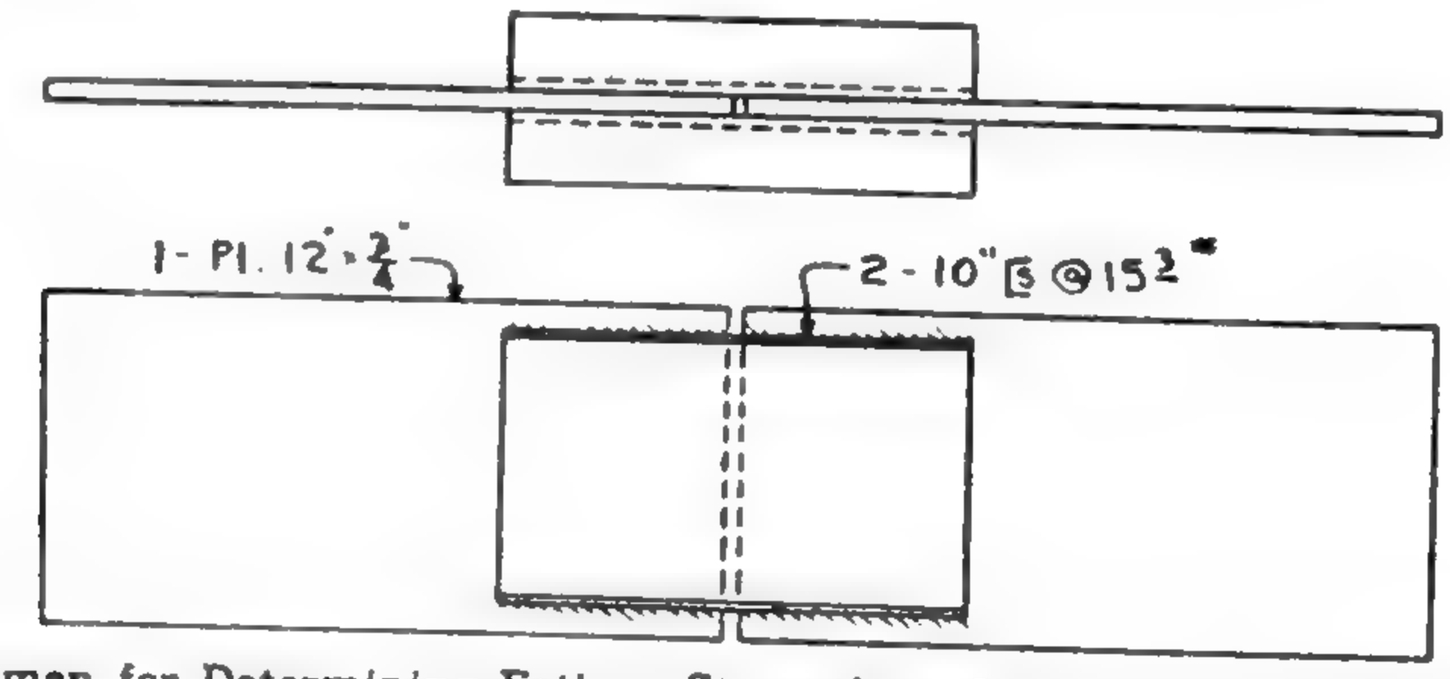

Fig. 6.—Specimen for Determining Fatigue Strength of Joint with Longitudinal Fillet Weld Connecting Channels and Plates

1. Failure in the deposited weld metal. The fatigue strength in this case depends upon the welding process and procedure (method of welding, kind of filler metal, treatment, etc.), base metal and quality of the weld. Porosity, slag inclusions and poor fusion lower the fatigue strengths through their effects as stress raisers. Although it is known that these defects lower the fatigue strength, there is virtually no quantitative experimental evidence available.
2. Failure in the line of fusion. In this case failure is usually the result of poor fusion, lack of penetration, microscopic cracks or some other cause which produces stress raisers.
3. Failure in the heat-affected zone.

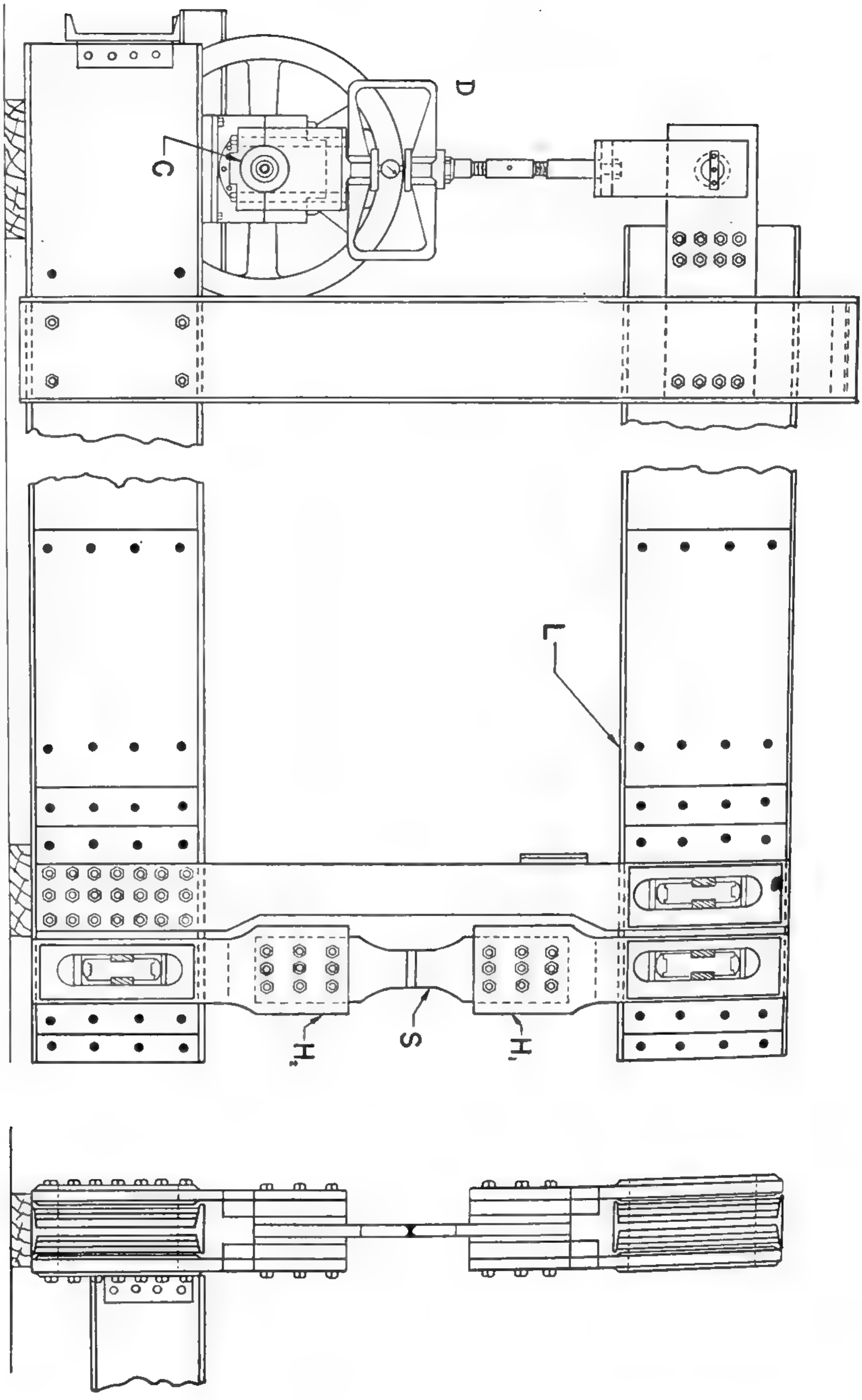

Fig. 7.—The Wilson Fatigue Testing Machine

The heat cycle accompanying welding produces a structural change immediately adjacent to the weld deposit. This structural change is a function of the welding process and procedure and the analysis of base metal. In some cases the heat-affected zone will have a higher fatigue strength than the original base metal, while in other cases it will have a lower fatigue strength.

4. Failure at the edge of the weld. Stress raisers at the edges of the weld caused by the joint design, weld contour and undercut frequently cause fatigue fractures to occur through the base metal at these points. Failures of this type are generally the combined result of the effects produced by the stress raisers and the heat-affected zone.

The published data on fatigue properties of welded joints show a wide scatter in the limits obtained. This scatter is largely the result of the welding procedures used in making the joints, the quality of the welds and the type and location of the defects causing the failures. In analyzing fatigue data, it is therefore important that as much as possible be known about the welding process, welding procedure, weld quality and types of failure.

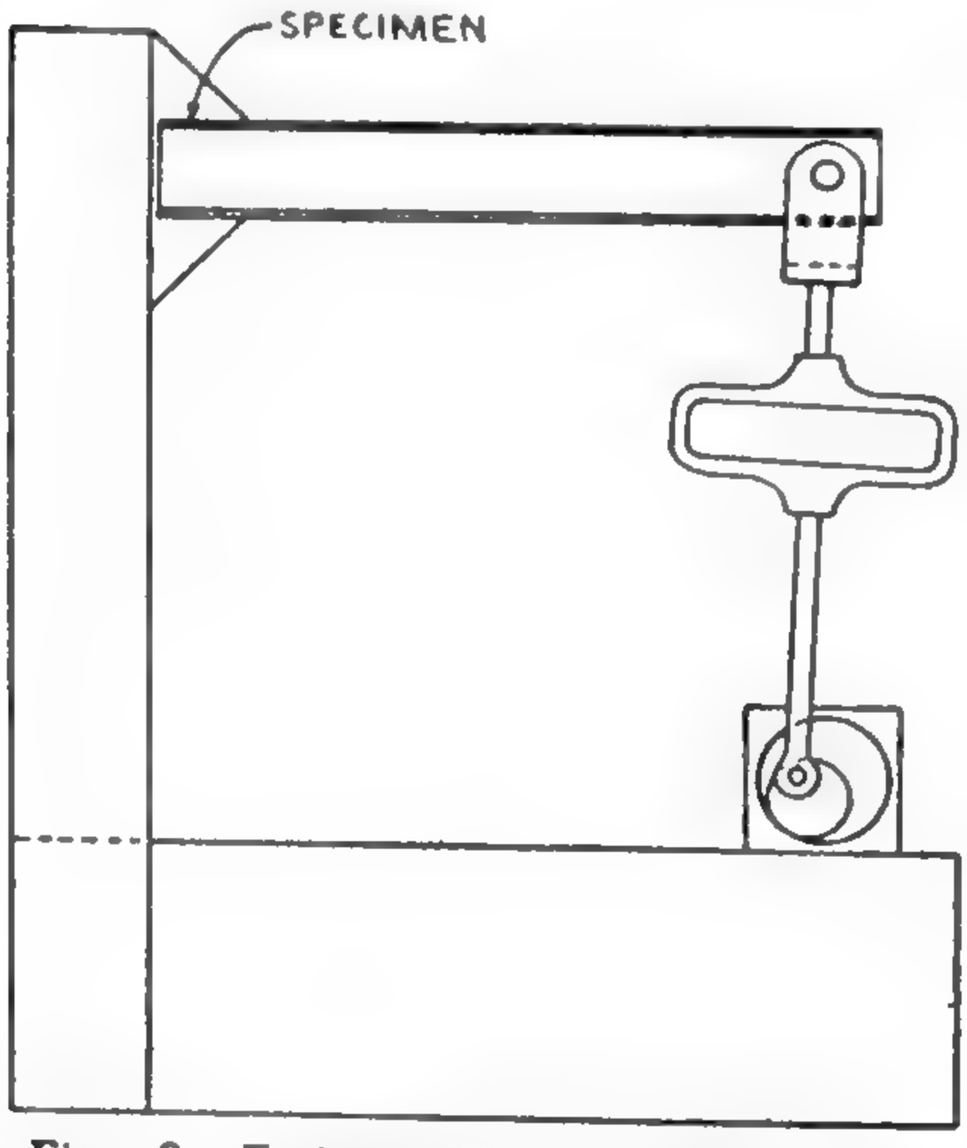

Fig. 8.—Fatigue Testing Machine for Subjecting a Beam-to-Column Connection to Pulsating or Reversed Bending

Fatigue Limits of Welds in Low-Carbon Steel

Tests of butt welds in $^{7}/_{8}$-in. steel plate conforming to ASTM Specifications A7 (with carbon not more than 0.25% and manganese not over 0.70%), welded under commercial conditions and in accordance with the American Welding Society *Standard Specifications for Welded Highway and Railway Bridges* show that *dependable* fatigue strengths may be anticipated in the as-welded condition as follows:

Zero to tension, 100,000 cycles—27,000 psi.
Zero to tension, 2,000,000 cycles—18,000 psi.

These values apply for both shop and field welding and for welds made in all positions. For butt welds having surface defects such as undercut or excessive reinforcement and for butt welds having incomplete fusion the fatigue strength cannot be predicted but will probably be less than the above values.

Results of torsional fatigue tests (shearing stress) of specimens from joints show about 25% lower efficiency than those shown in tension-compression or in rotating-beam fatigue tests. The fatigue limit of metals has been found by many experimenters to be lower in torsion than in flexure or axial stress.

Tests of specimens from welds made with different sizes of electrodes show variation in the fatigue strength of the weld which can probably be ascribed to variations in workmanship. A reverse run (re-welding the root) raised the fatigue strength in pulsating tensile tests and in reverse bending tests 10 to 20%. The reverse run is helpful because it eliminates almost entirely the stress-raising effect of the usual notch at the root of the weld, and not because it refines the grain structure.

Compressive tests of butt welds in bridge steel (A7) $^{7}/_{8}$-in. thick have indicated the following dependable fatigue strengths:

Zero to compression, 100,000 cycles—49,500 psi.; 2,000,000 cycles—33,000 psi.
Compression to tension $^{1}/_{4}$ as great. 100,000 cycles—27,600 psi.; 2,000,000 cycles—18,400 psi.
Compression to tension $^{1}/_{2}$ as great, 100,000 cycles—20,900 psi.; 2,000,000 cycles—14,000 psi.
Compression to tension $^{3}/_{4}$ as great, 100,000 cycles—17,700 psi.; 2,000,000 cycles—11,800 psi.

Compression to equal tension (full reversal), 100,000 cycles—16,500 psi.; 2,000,000 cycles—11,000 psi.

The fatigue strength for 2,000,000 cycles of loading in which both the maximum and minimum stresses are compression will exceed the yield point of the base metal.

Biaxial stresses have been used in fatigue tests of welded low-carbon steel tubing. The maximum stress theory was found to apply and the fatigue strength of the welded tubes, for a principal stress ratio, r, of 1, was 15% less than for unwelded tubes.

Resistance Welding.—Fatigue failures in tests of spot-welded, low-alloy steel (Cor-Ten) and spot-welded 18–8 stainless steel 0.48-in. thick occurred in the heat-affected zone at the notch formed by the junction of the weld nugget with the two sheets. Good spot welds developed 20,000 psi, at 10,000,000 cycles. An investigation of the fatigue strength of spot welds in the aluminum alloy 24S-T, 0.032 to 0.064-in. thick, showed that the size of the spot weld was most important. Large welds were better in fatigue than small welds. For high stresses and small welds, soundness is important. For large welds and stresses close to the fatigue limit, soundness is not a major factor. Flash welds had excellent fatigue strength particularly when welding was followed by quenching and drawing.

Miscellaneous Test Results

The fatigue limit of a sound deposit of weld is about the same as that of rolled steel of the same chemical composition. The presence of porosity or inclusions in a weld metal deposit may lower the fatigue limit 15% or more.

In order of their importance the most common flaws that have been found to cause low fatigue strength are: (1) lack of fusion, especially at the root of the weld; (2) slag inclusions; (3) blow holes. Some commercial welds made in the field and containing these flaws have developed only 64% of the fatigue strength of flawless welds.

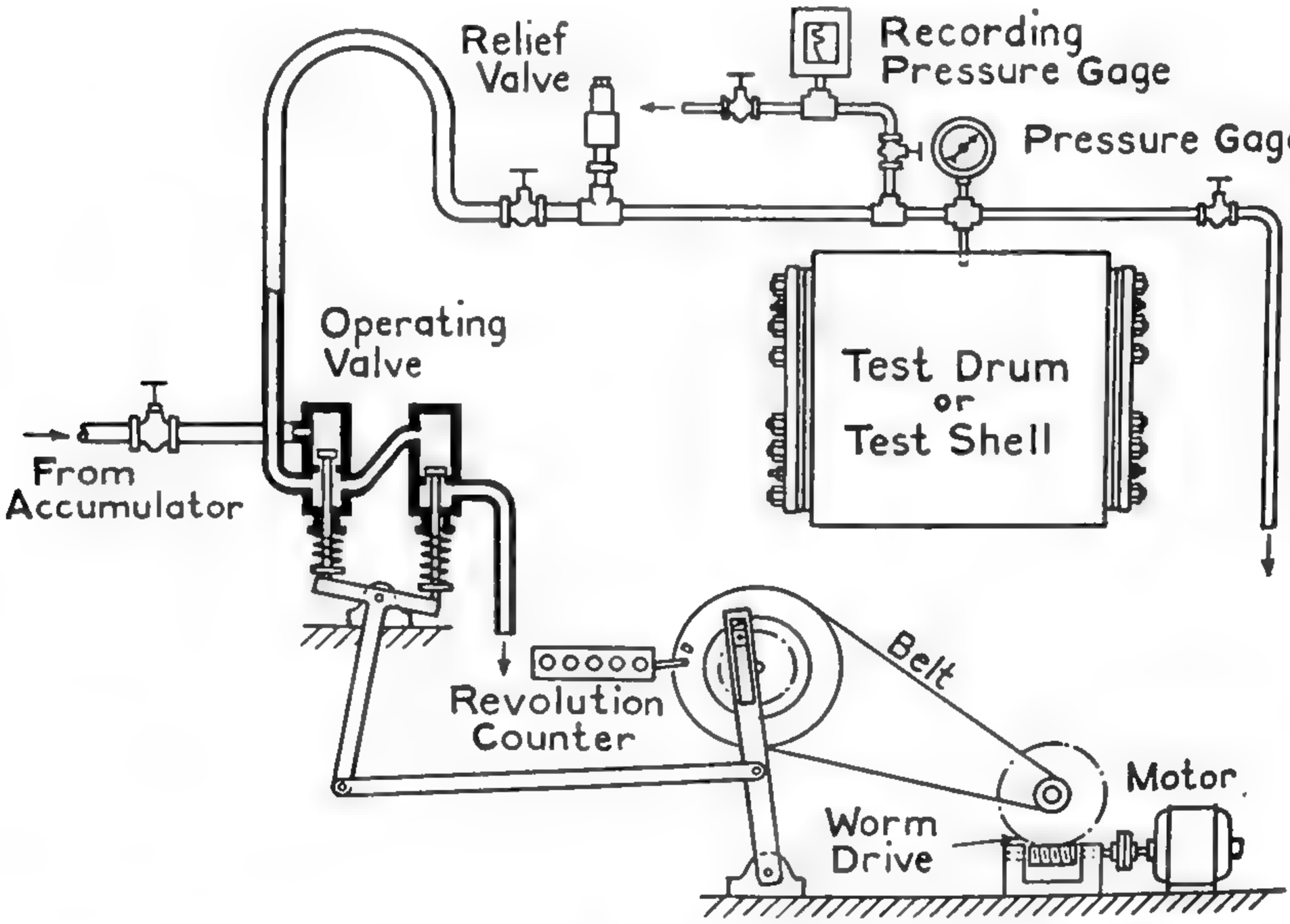

Fig. 9.—Test Rig for Applying Repeated Cycles of Hydraulic Pressure to Pressure Vessels

The fatigue properties of atomic hydrogen welds are about the same as those of gas welds and arc welds. Resistance welds, however, have shown remarkably high fatigue limits, especially in tests in corrosive media. The torsional fatigue limit for flash welds in mild steel is about the same as that for the base metal. Pulsating tensile fatigue limits

(r very small) for carbon-arc welds range from 14,000 to 21,500 psi., the value depending upon the technique of the welder. The fatigue limit of a brazed joint in mild steel of $^3/_4$ by $^3/_8$-in. cross section was found to be 20,000 psi., when tested in reverse bending.

Influence of Low Temperatures

Tests of welds at temperatures down to —80°F. show no pronounced change in fatigue limit as the temperature is lowered. However, the results are obscured by the temperature rise in the specimen at stresses close to the fatigue limit. Preliminary results indicate that the fatigue limits of welds in mild steel differ but slightly from those of unwelded steel.

Influence of Mechanical Treatment

Peening.—One investigator found that unmachined all-weld metal deposited by bare electrodes had a fatigue limit of 18,000 psi. in rotating-beam (cantilever) tests. Peening each layer of deposited metal raised the fatigue limit to 20,000 psi. However, similar improvement has not been obtained in welds made with covered electrodes.

Hot Forging.—Hot forging raises the fatigue limit but, because of grain growth, the increase due to forging at temperatures of about 2190°F. (1200°C.) is not great. Hot forging increases the fatigue limit of backhand gas welds by 20%; of forehand welds by only 10%. Forging of welds in mild and alloy steels made with coated or cored electrodes (0.07% C, 0.65 to 2.8% Mn) increases the fatigue limit from 75 to 100%.

Machining.—Experiments show that for medium and high-quality arc welds, butt or fillet, in structural steel, intelligent removal by machining of undercutting and other surfaces notches or reinforcement raises the fatigue limit about 25%. For welds of poor quality having many inclusions, machining is of no appreciable advantage. One investigator reports 40% increase in pulsating fatigue limit of parallel shear fillet welds the inner ends of which have been machined, over the fatigue limit of unmachined specimens.

Influence of Annealing and Stress Relief and Residual Stress

Annealing.—Annealing at from 1616 to 1688°F. (880 to 920°C.) lowers the fatigue limit of welds having a nitrogen content above about 0.04% N but raises the fatigue limit if the nitrogen content is below 0.04%. The difference in fatigue limit between the as-welded and the annealed specimens is not more than 3000 psi.

Stress-Relief Heat Treatment.—Reports on the effect of stress relief (by heating to about 1100°F.) on the fatigue limit of welds are somewhat conflicting. It seems quite possible that stress relieving increases the notched-bar impact values more than it does the fatigue strength values.

Shrinkage Stresses.—Internal stresses in ductile welds are diminished by the minute plastic yielding which occurs under repeated loads even though the computed stresses are below the static yield strength of the metal. For brittle welds internal stresses are effective in lowering the fatigue limit.

Influence of Alloying Elements

Carbon Content.—A carbon content of the base metal between 0.25 and 0.60% has only a slight effect on the reverse bend fatigue limit of groove welds.

Alloy Steels.—Welds in low-alloy steel have satisfactory values of fatigue limit but low-alloy steels have only slight advantage over mild steel, except at high values of superimposed tension, under which condition the high yield point of the low-alloy steels becomes important.

Stress-relieved and machined butt welds in carbon-silicon and manganese-molybdenum steel plates $^3/_4$ to 1-in. thick had essentially the same fatigue strengths as unwelded plate. Joints in $^3/_4$-in. 5% Cr–0.5% Mo steel plates welded with 25–20 austenitic steel electrodes, when tested in the as-welded condition with reinforcement machined off, developed an axial tension fatigue limit of 31,000 psi.

Welds in 0.32% C and 3.4% Ni base metal made with chromium-molybdenum electrodes showed higher fatigue limits than welds in the same base metal made with chromium-nickel or 3.5% nickel electrodes.

Welds in plate containing 3.5% Ni withstood 20 times as many cycles of stress at 30,000 psi. as did welds in plain medium-carbon plate. For tests of both plates a low-carbon electrode (0.13–0.18% C) gave better results than a chromium-vanadium electrode (0.89% Cr, 0.15%

V) or a nickel-chromium electrode (1.0% Ni, 0.5% Cr).

Fatigue Strength of Structural Parts

A comprehensive series of fatigue tests of double-vee butt welds in $^{7}/_{8}$-in. carbon steel plates has been made as a part of the work of Committee F, Fatigue Committee (Structural) Welding Research Council. The details of the specimens are shown in Fig. 5. The plates had a carbon content of 0.25% and a manganese content of 0.48%. All welds were made in the flat position by a qualified welder using an all-position electrode. Radiographs were taken of all specimens and the welds were found to be free of all but minor defects and were probably more uniformly good than most commercial welds. The fatigue strength was determined for failure at both 100,000 and 2,000,000 cycles. The stress ranges used included tension to an equal compression, 0 to a maximum tension and a maximum tension to a tension one-half as great. Some specimens were tested in the as-welded condition, some were stress-relieved and some had the reinforcement planed off flush with the base plate. Similar tests were also made of specimens similar to the one shown in Fig. 5, except that each consisted of a plate without a weld, the specimens being cut from the same base metal as the plates of the welded joints. A summary of the results of the tests is given in Table 2. The same data are presented graphically by the diagrams of Fig. 10. The small circles connected with broken lines represent the results of the tests and the full lines represent the empirical equation $(FL)' = 3(FL)/(2 - r)$, in which (FL) is the fatigue strength under complete reversal, r is the ratio of the minimum to the maximum stress (negative for a reversal of stress) and $(FL)'$ is the fatigue strength for a given r. The numeral adjacent to a small circle indicates the number of tests averaged.

The following conclusions, based upon the values given in Table 2 and Fig. 10, are quoted from the report of the tests:

"For specimens in the as-welded condition, the values of the fatigue strength for a cycle in which the stress varied from tension to an equal compression were 22,300 psi. for failure at 100,000 cycles and 14,400 psi. for failure at 2,000,000 cycles; and for a cycle in which the stress varied from zero to tension the values of the fatigue strength were 33,100 psi. for failure at 100,000 cycles and 22,500 psi. for failure at 2,000,000 cycles.

"For specimens in the as-welded condition except that the reinforcement had been machined flush with the base plate on both sides, the values of the fatigue strength for a cycle in which the stress varied from tension to an equal compression were 28,900 psi. for failure at 100,000 cycles and 16,850 psi. for failure at 2,000,000 cycles. These values are considerably higher than corresponding values reported in the preceding paragraph for similar specimens with the reinforcement on.

"A comparison of the fatigue strength of butt welds that have been stress-relieved by heat treatment with the fatigue strength of those that have not been stress-relieved indicates that stress-relieving did not affect the fatigue

Table 2—Fatigue Strength of Butt Welds in $^{7}/_{8}$-In. Carbon-Steel Plate

Description of Specimen	Fatigue Strength, 1000 Psi. — Tension to an Equal Compression		Zero to Max. Tension		Tension to Tension ½ as Great	
	N = 100,000	N = 2,000,000	N = 100,000	N = 2,000,000	N = 100,000	N = 2,000,000
As-welded	22.3	14.4	33.1	22.5	53.3	36.9
Reinforcement on, stress relieved	21.3	15.1	31.9	23.7	..	37.6
Reinforcement machined off, not stress-relieved	28.9	..	48.8	28.4	..	43.7
Reinforcement machined off, stress-relieved	24.5	16.6	49.4	27.8	..	42.6
Reinforcement ground off, not stress-relieved	26.8	..	44.5	26.3	..	..
Plain plate, mill scale on	27.7	17.1	49.8	31.7	..	50.0
Plain plate, mill scale machined off, surface polished	..	..	59.6	..	..	..
Butt weld, reinforcement and mill scale machined off, surface polished	..	..	53.9	..	..	..

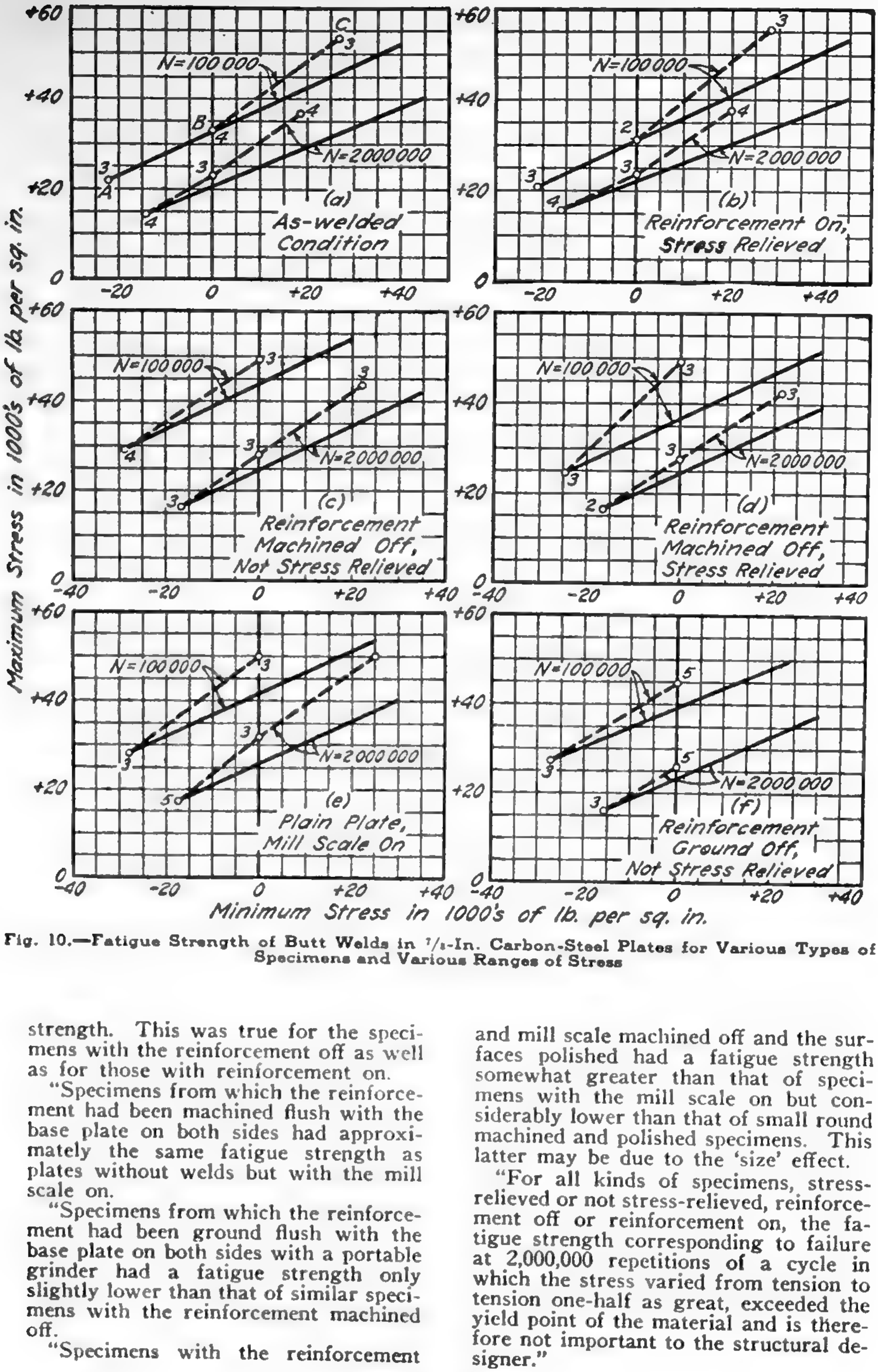

Fig. 10.—Fatigue Strength of Butt Welds in 7/8-In. Carbon-Steel Plates for Various Types of Specimens and Various Ranges of Stress

strength. This was true for the specimens with the reinforcement off as well as for those with reinforcement on.

"Specimens from which the reinforcement had been machined flush with the base plate on both sides had approximately the same fatigue strength as plates without welds but with the mill scale on.

"Specimens from which the reinforcement had been ground flush with the base plate on both sides with a portable grinder had a fatigue strength only slightly lower than that of similar specimens with the reinforcement machined off.

"Specimens with the reinforcement and mill scale machined off and the surfaces polished had a fatigue strength somewhat greater than that of specimens with the mill scale on but considerably lower than that of small round machined and polished specimens. This latter may be due to the 'size' effect.

"For all kinds of specimens, stress-relieved or not stress-relieved, reinforcement off or reinforcement on, the fatigue strength corresponding to failure at 2,000,000 repetitions of a cycle in which the stress varied from tension to tension one-half as great, exceeded the yield point of the material and is therefore not important to the structural designer."

Effects of Periods of Rest Upon Fatigue Strength of Groove Welds in Carbon Steel Plates

The question has been raised as to whether or not the results of fatigue tests run continuously in a laboratory are applicable to field structures which are subjected to intermittent service. Committee F planned a series of tests to answer this question. The specimens consisted of single-vee butt welds in $^1/_2$-in. steel plates for which the carbon, manganese and silicon contents (%) were 0.27, 0.45 and 0.01, respectively. The specimens were 3 in. wide at the weld. The following paragraphs are quoted from the report:

"The method of making the tests was as follows:

"Nine specimens, as nearly as possible identical, were selected for a series to be tested at a given cycle, the maximum stress in the cycle and the ratio of the minimum to the maximum stress being the same for all specimens. Three were tested continuously, three were tested with 5-min. rest periods following each 100 cycles and three were tested with 30-min. rest periods following each 100 cycles. Some series were planned for failure at 100,000 cycles, others for failure at 2,000,000 cycles. The latter, however, did not include the tests with 30-min. rest periods because of the great length of time that would be necessary for such a test.

"A summary of the results is given in Table 3, each value representing the average of three tests.

"The data contained in the table indicate that rest periods decrease the fatigue strength, and that the longer the rest period the less is the indicated fatigue strength. The average difference between the rest and no-rest strengths was 5%; and the maximum difference was 10%.

"The Committee interprets the results of these tests to indicate that rest periods have no significant effect upon the fatigue strength of welded joints in such a steel, when these joints are made and tested under conditions approximately those met in general structural work; and that this conclusion may be extended to welded joints in steel of the standard grade for bridges and buildings."

Table 3—Effect of Rest Upon Fatigue Strength of Butt Welds in $^1/_2$-In. Carbon-Steel Plate

	Stress in Thousands of Psi.	Fatigue Strength[a] N = 100,000[b] No Rest	N = 100,000[b] 5 Min. Rest	N = 100,000[b] 30 Min. Rest	N = 2,000,000[b] No Rest	N = 2,000,000[b] 5 Min. Rest
Complete reversal	+20.0 to −20.0	20.1	20.5	19.8	..	..
		..	..	20.2	..	..
	+16.0 to −16.0	..	..	..	13.4	14.2[c]
		..	..	..	..	13.8
Zero to max. tension	0 to +27.0	..	..	..	25.6	23.8
	0 to +30.0	..	34.3	..	27.2	..
	0 to +35.0	37.6	..	34.9	..	..

[a] Each value represents the average of three tests.
[b] N represents the number of cycles for fracture.
[c] Two groups of three tests each at this rest period with average fatigue strengths as shown.

Effect of Transverse Fillet Welds On Fatigue Strength of Steel Plates

Tests were planned by Committee F to determine the effect of transverse fillet welds upon the fatigue strength of steel plates. Three types of specimens were used, the details of which are shown in Fig. 11. Type I was a continuous plate without welds or joints and with mill scale on both sides; Type II had a narrow transverse plate attached to one side of the main plate with two transverse fillet welds; Type III had transverse plates attached to both sides of the main plate. The main plate was continuous for all three types of specimens.

Specimens of each of the three types were made of a medium-grade carbon steel and a low-alloy steel. Each of the six groups contained six similar specimens that were tested in fatigue on a cycle in which the stress varied from tension to an equal compression.

The carbon-steel plates had a yield point of 34,500 psi., an ultimate strength of 58,700 psi., an elongation in 8 in. of 30.7% and a reduction of area of 55.1%.

The alloy steel plates had a yield point of 59,100 psi., an ultimate strength of 78,900 psi., an elongation in 8 in. of 20.5% and a reduction of area of 61.5%.

A summary of the results of the tests

is given in Table 4, each value being the average of three tests.

The following paragraphs are quoted from the full report of the tests.

"The fatigue strength of the Type I and Type II specimens was significantly greater for the alloy steel than for the carbon steel. For the Type III specimens the fatigue strength for failure at 100,000 cycles was approximately the same for both steels but, for failure at a larger number of cycles, the fatigue strength was somewhat less for the alloy than it was for the carbon steel.

"The fatigue strength of specimens made of the alloy steel was considerably greater for the Type II specimens and somewhat less for the Type III specimens than the fatigue strength of single-vee butt welds connecting plates of the same alloy steel."

In a study of the fatigue strength of weldments used to reinforce and repair steel bridge members, it was found that adding butt straps attached with fillet welds across butt welds connecting two plates greatly reduced the fatigue strength of the joint. Attaching partial length cover plates to 12-in., 31.8-lb. I-beams either by welding or riveting greatly reduced the total fatigue strength of the beams. Various expedients for reducing the stress-raising factors at the ends of the partial-length cover plates were ineffective.

The unit flexural fatigue strength of 12-in., 31.8-lb. I-beams reinforced with full-length cover plates, $^{9}/_{16}$-in. thick, attached with continuous $^{5}/_{16}$-in. fillet welds was considerably less than the unit flexural fatigue strength of the same beams in the as-rolled condition. The total fatigue strength of the reinforced beam was only slightly greater than for the unreinforced beams.

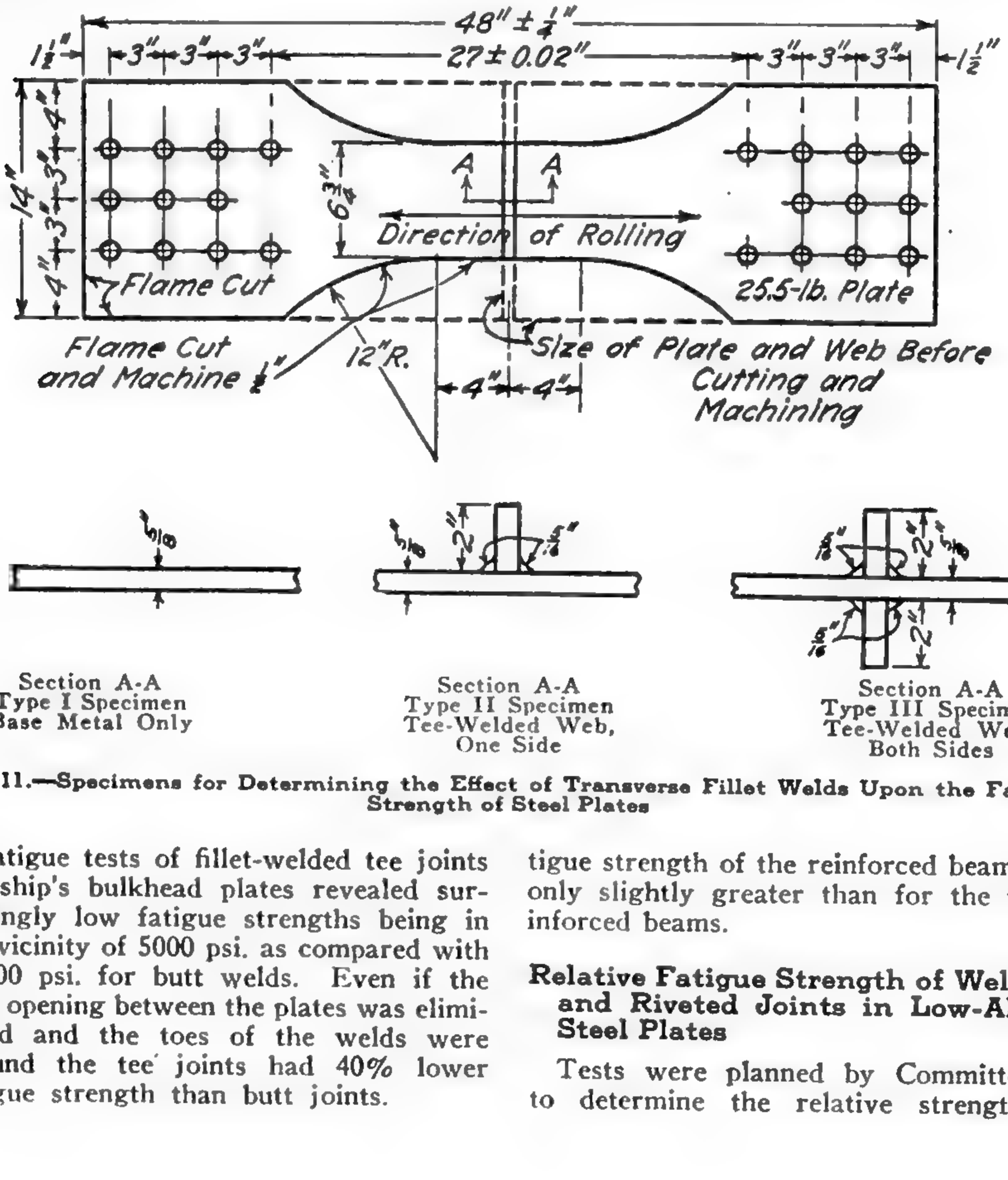

Fig. 11.—Specimens for Determining the Effect of Transverse Fillet Welds Upon the Fatigue Strength of Steel Plates

Fatigue tests of fillet-welded tee joints for ship's bulkhead plates revealed surprisingly low fatigue strengths being in the vicinity of 5000 psi. as compared with 25,000 psi. for butt welds. Even if the root opening between the plates was eliminated and the toes of the welds were ground the tee joints had 40% lower fatigue strength than butt joints.

Relative Fatigue Strength of Welded and Riveted Joints in Low-Alloy Steel Plates

Tests were planned by Committee F to determine the relative strength of

Table 4—Fatigue Strength of Plates with Transverse Fillet Welds

Steel	Type of Specimen	Average Fatigue Strength, Thousand Psi. N = 100,000[a]	N = 2,000,000[a]
Plain carbon	I	25.8[b]	22.8
	II	25.4	18.9
	III	22.9	13.1
Low alloy	I	35.3	26.4
	II	31.7	23.9
	III	22.2	10.1

[a] N denotes the number of cycles of stress for failure.
[b] Each value is the average of three tests.
NOTE: During a cycle the stress varied from tension to an equal compression.

welded and riveted joints connecting plates of a low-alloy steel of structural grade. There were nine each of riveted and welded specimens; six of the riveted specimens were subjected to fatigue tests and three to static tests. Of the welded specimens, seven were subjected to fatigue tests and two to static tests. The object of the static tests was to determine the strength of the joint and, for the riveted joints, to determine the load-slip relation.

All specimens were made of low-alloy structural steel plates approximately $^1/_2$-in. thick and weighing 21 lb. per sq. ft. and having C, Mn and Si contents of 0.16, 1.27 and 0.20%, respectively.

The riveted joints were of the double-strap butt type with $^3/_4$-in. manganese-steel rivets. The driven heads of the rivets were countersunk and chipped; the manufactured heads were of the button type.

The welded joints were of the single-vee butt weld type welded in the flat position using a covered electrode such as is usually used for welding carbon steel plates.

The following conclusions are quoted from the full report of the tests.

"The low-alloy structural steel plates had a static strength of 83,000 psi. based on the gross area when fabricated by welding and of 64,800 psi. when fabricated by riveting. The strength of the latter based on the net section was 85,000 psi.

"The low-alloy structural steel plates had a fatigue strength based on the gross area and corresponding to failure at 100,000 cycles of 25,000 psi. when fabricated by welding and of 19,800 psi. when fabricated by riveting. For failure at 2,000,000 cycles, the corresponding values were 15,000 psi. and 13,800 psi. for welded and riveted joints, respectively. These values of the fatigue strength are for a cycle in which the stress varied from tension to an equal compression.

"The fatigue cracks in the riveted specimens passed through the holes in the outer row. Those in the welded specimen began at the edge of the deposited metal where the abrupt change in section acted as a stress raiser that extended the full width of the specimen."

Fatigue Strength of Machine Parts

The importance of fatigue strength of welded joints is recognized by the designer of welded machinery and in some codes maximum working stresses in fatigue have been established. Very few fatigue tests have been made on machines and in most cases values obtained from simple joint tests are used.

When designing a welded structure subjected to fatigue it is important to keep in mind the harmful effect of stress raisers. Reinforcements, undercut, incomplete fusion, incomplete penetration and porosity are all stress raisers. Double welded joints are the best insurance against incomplete penetration at the root of a weld.

Fillet welds, because of their inherent shape, are prime offenders from the standpoint of stress raisers. The stress concentration at the toe of a fillet weld may lower the fatigue limit of the base metal at that point to 10,000 psi. After a certain size weld is reached, the base metal becomes the critical section and increasing the weld size will not increase the strength of the joint.

Special shaped butt straps with rounded or beveled ends are often used to reduce the stress raisers obtained by plain parallel and transverse fillet welds. Intermediate stress plates have been used between members, but they have been found to have no effect on increasing the fatigue limit of the joint.

Reinforcing a butt joint with fillet welded butt straps has little or no effect in increasing the fatigue strength of the joint. In many cases the strength may actually be greatly reduced.

The fatigue limit of intermittent fillet welded joints subjected to tension-compression loading is lower than that of a continuously welded joint. One investigator recommends, for intermittent and continuous fillet welds, allowable stresses 60 and 85%, respectively, of the allowable stress in the base metal.

Investigations to determine the feasibility of welding wheel spokes directly to a 0.45% C shaft rather than to an intermediate hub indicate that the fatigue strength of the shaft is lowered to 7200 psi. because of the stress raisers. Changing the number of spokes from 4 to 6 had no effect. Tests on arc and gas-welded tubular triangle assemblies, and similar assemblies including brazed joints, showed the importance of design and heat treatment in securing high fatigue strength.

Fatigue Strength of Welded Railroad Rails

Tests of full-section specimens of welded railroad rails, sponsored by the Association of American Railroads, have been carried on in the Talbot Laboratory at the University of Illinois. The testing machine used for these tests is shown in Fig. 12. The welded joint specimen S is pulled backward and forward under the wheel *W*, the load on which can be varied from 0 to 75,000 lb. by means of the screw jack *J* and the lever *L*. The load is measured by the compression of the spring *P*. The stroke of the machine is 12 in., and the speed 60 rpm.

Three or more specimens of each type of welded joint were tested for each of two weights of rail, 112 and 131 lb. per yard (except for the flash welded specimens which were furnished for 131-lb. rails only). The specimens of each group were tested under a series of loads, 75,000 lb. for the first specimen, and successively lower loads for the other specimens. Then *S-N* diagrams were drawn. Figure 13 shows *S-N* diagrams for the 112-lb. specimens. The fatigue strength was determined for 2,000,000 cycles of stress, and the cycle of stress was a cycle of wheel load, bending moment and shearing stress ranging from zero to a maximum with the rail head in tension.

Extensive field tests of stresses set up in rails under traffic indicate that in the normal life of a rail on straight track about 100,000 cycles of heavy wheel load (40,000 lb. or higher) might be expected. The selection of 2,000,000 cycles for determining the fatigue strength is somewhat arbitrary, and the determination of fatigue strength is less definite than is the case for small specimens, but the results are believed to have a comparative value for the different types of weld.

Three types of fractures were found in the specimens tested; (1) failure by flexural stress starting from a point on the tread of the rail, (2) failure by shearing stress in the web and (3) failure by a transverse fissure starting from some imperfection in the interior of the head of the rail. Rolling-load tests of short lengths of rail without any welded joint were also made. The chemical composition of the steel in the rails ranged between the following values: C, 0.70–

Table 5—Endurance Limits for 2,000,000 Cycles of Rolling Wheel Load on Welded Rail Specimens and Rail Specimens Without Welds

Type of Joint	At Fatigue Limit—Wheel Load, Lb.	At Fatigue Limit—Maximum Bending Moment, In.-Lb.	At Fatigue Limit—Maximum Tensile Stress (Flexural), Psi	At Fatigue Limit—Maximum Shearing Stress, Psi.	Ratio of Strength to That of Rail without Weld, %
Rail, 112 lb. per yard					
Rail without weld	62,500	750,000	41,600	25,400	100
Gas weld (Process A)	39,000	390,000	21,600	15,800	62[a]
Gas weld (Process B)	28,000	280,000	15,600	11,400	45[a]
Thermit weld	49,000	490,000	27,200	20,000	78[a]
Flash weld	No specimens of welded 112 lb. rails				
Pressure gas weld	58,000	580,000	32,200	23,600	78[b]
Rail, 131 lb. per yard					
Rail without weld	69,200	830,000	36,600	21,300	100
Gas weld (Process A)	40,000	400,000	17,600	12,300	58[a]
Gas weld (Process B)	19,000	190,000	8,400	5,900	27[a]
Thermit weld	55,000	550,000	24,200	17,000	79[c]
Flash weld	75,000	750,000	33,000	23,100	90[b]
Pressure gas weld	80,000	800,000	35,200	24,700	96[b]

[a] Failure by internal fissure; strength ratio based on wheel load.
[b] Failure by flexural stress; strength ratio based on bending moment.
[c] Failure in web (shearing stress); strength ratio based on wheel load.
NOTE: In the rolling-load test the head of the rail specimen is subjected to cycles of tensile stress (flexural) varying from zero to a maximum.

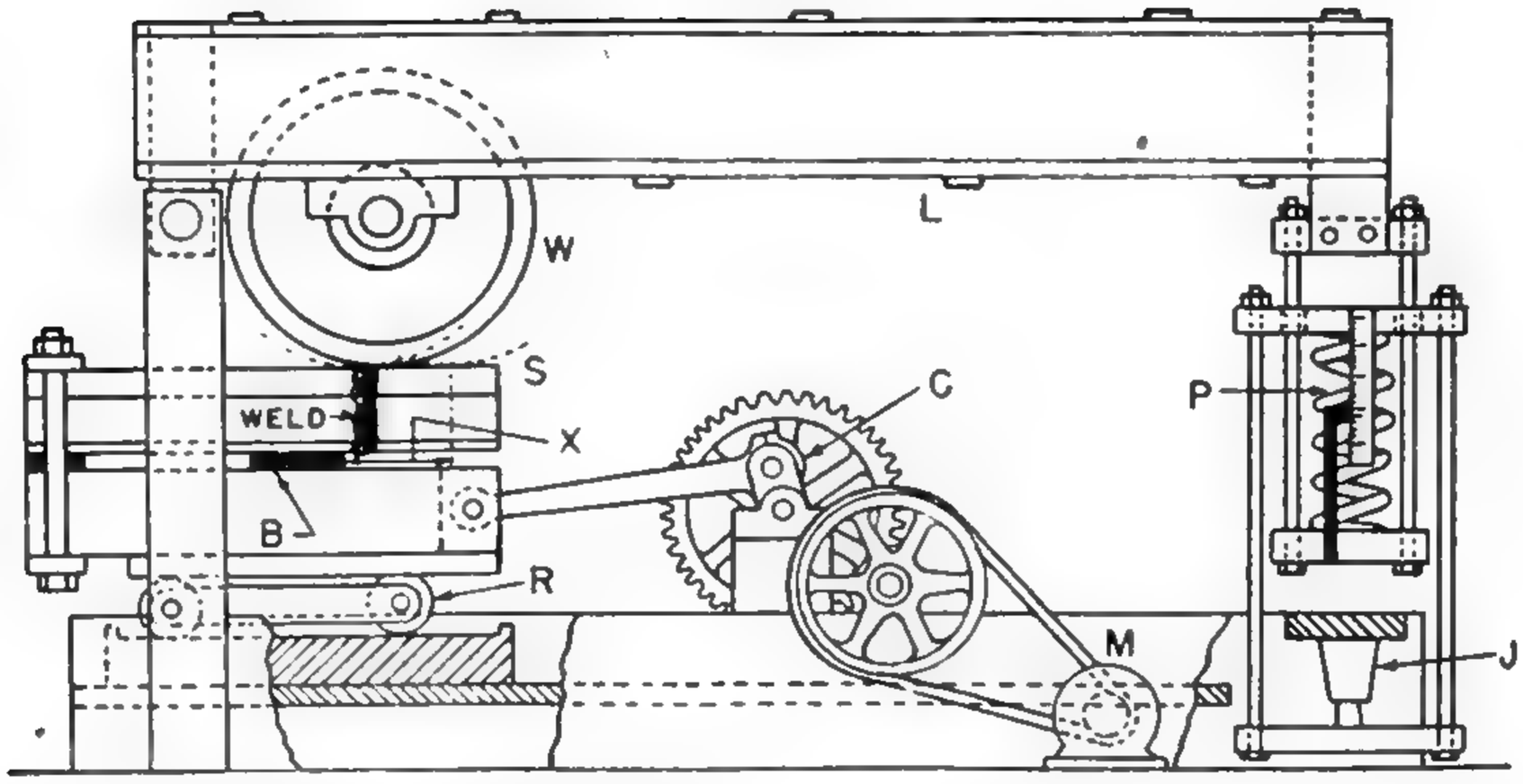

Fig. 12.—Rolling-Load Testing Machine for Fatigue Tests on Welded Rails

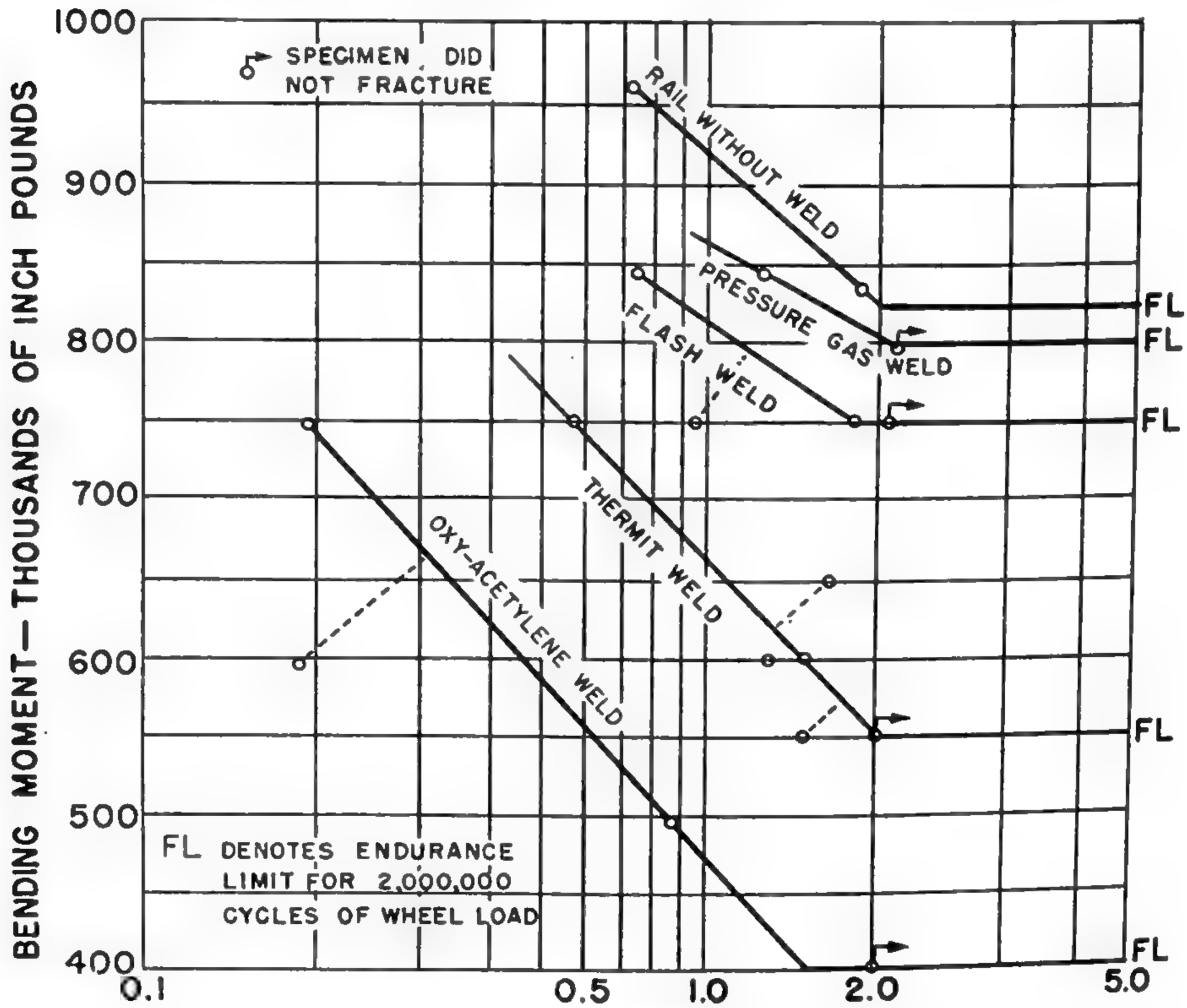

Fig. 13.—S-N Diagrams for Fatigue Tests of Welded Rail

0.73%; Mn, 0.76–0.80%; Si, 0.15–0.20%; P, 0.020–0.023%; S, 0.022–0.037%.

Table 5 shows the ratio of fracture strength under the rolling-load test of rails with welded joints and rails without welded joints. The values of strength are based on a life of 2,000,000 cycles of rolling load.

While these rolling-load tests of welded rails are too few to serve as a basis of any precise evaluation of the strength of welded rail, yet they offer some evidence that under the repeated loading to which railroad rail is subjected the flash welded rails and the pressure-welded rails using gas (acetylene) for heating developed a minimum of 78% and an average of 88% of the strength of unwelded rail. The thermit welds developed about 78% of the strength of the unwelded rail. The welds (oxy-acetylene) without pressure were weaker than the other types of welded rail.

Summary

The fatigue strength of machined flawless butt welds is the same as unwelded plate of the same tensile strength, at least up to about 80,000 psi.

Removal of surface irregularities, such as reinforcement, is the most important factor in developing the highest fatigue strength in welds that are otherwise sound. Owing to unavoidable notch effects, fillet welds have only about 50 to 70% of the fatigue strength of butt welds of equivalent static strength. While physical notches have a large effect on fatigue, so-called metallurgical notches created by differences in microstructure in weld and heat-affected zone have little effect, at least in mild steel.

Although the test results show that butt welds are preferable to fillet welds, it should be borne in mind that there are many inherent and unavoidable irregularities in shape in fabricated structures. These irregularities are necessary elements in the design, yet each introduces stress concentrations as serious as a fillet weld. It is at these points that the flexibility of welded design with oxygen cutting permits the greatest possible reduction in the stress concentrations and the greatest possible improvement in the overall fatigue strength.

C. CORROSION RESISTANCE

GENERAL

In the case of many metals and alloys under many of the common conditions of exposure, no special attack at or adjacent to the welds ordinarily occurs. However, since the weld metal often differs chemically or metallurgically from the base metal, in specific solutions or under certain conditions of exposure special attack may occur at or adjacent to the welds. As a rule there is less likelihood of such special attack if the weld metal is of the same composition as the base metal, particularly if the welded parts are annealed or given a solid-solution heat treatment after welding. In environments where steel is protected from attack by an adherent film or scale, heat treatment of welded assemblies may be desirable to restore a lamellar pearlitic structure which holds protective films better than a distorted pearlitic structure resulting from the heat effect of welding. It is important to obtain welds that are free from pinholes, cold shuts, trapped slag or other mechanical defects. Such imperfections may well provide a starting point for attack by corrosion.

FACTORS AFFECTING CORROSION

Design of Joints

The design of a joint often has a bearing on its resistance to a specific exposure. In general, lap joints, through which moisture can penetrate and be trapped between the faying surfaces, are more subject to selective attack than are other types of joint that do not permit the access of liquid between the faying surfaces. The special attack occurring at such lap joints is probably the result of concentration cells set up between the liquid at faying surfaces and the liquid in contact with the exposed surfaces of the weld metal. As is mentioned subsequently, the presence of residual flux sometimes causes special corrosion. Joints designed so that flux can be easily removed are, therefore, less likely to suffer attack from this cause than are joints from which it is impossible to completely remove residual flux.

Flux Removal

Many types of fluxes are corrosive to the metals or alloys with which they are used. Therefore, it is important in most cases that residual flux be removed from the metal surface immediately after the welding operation. Methods of removal generally employed include mechanical methods such as scratch brushing, rinsing or scrubbing with water, and exposure to acid or other chemical dips. The best method to use in any given case depends on the metal or alloy that has been welded and the type of joint made. (Refer to the chapters on the metals for more detailed information.)

If the weldment is to be painted subsequently or given chemical or anodic treatments, flux removal usually is especially desirable, since residual flux can cause blistering of the paint and severe local attack during the chemical or anodic treatments.

Stress Corrosion

It is well known that stress may influence corrosion of the material to which it is applied and, since local stresses, such as may be developed in welding operations, are likely to have more adverse effect than uniformly distributed stresses, it is frequently desirable to give welded structures a stress-relief treatment or stress-equalizing anneal after welding where corrosion is a factor.

Metals and alloys vary considerably with respect to their susceptibility to stress corrosion, and with each material there is a limited number of specific corrosive media in which stress corrosion is most likely to occur. Consequently, it is necessary to be guided by past experience and manufacturers' recommendations in determining whether stress relief after welding must be employed in any given case.

The substitution of welded for riveted joints has been found to be useful in removing opportunities for concentration of salts in crevices, a contributing cause of caustic embrittlement, which is a particular form of stress corrosion often encountered in steel boilers.

The possibility of stress corrosion of welded structures should be considered in planning and carrying out corrosion tests leading to the choice of material for a service in which there has been no past experience.

MATERIALS

Steel, Cast Iron and Wrought Iron

Welds in 6-in. diam. pipes made of seamless steel, cast iron and wrought iron, have been exposed to atmosphere, soil immersion, alternating tap water and atmosphere, salt spray, electrolysis in salt water and 15% HCl. Arc welds with covered electrodes and gas welds in steel both resisted corrosion under these exposures equally as well as the base metals. Arc welds with bare electrodes were attacked much more severely than the base metal. With the covered electrodes there was no difference in the corrosion resistance of arc welds made with direct and with alternating current. Alloy cast-iron welding rod has been found to eliminate galvanic corrosion sometimes encountered with welds on cast iron made with plain iron rod. Similarly good results have been secured with welds on cast iron made with high nickel alloy rods.

Arc welds in mild steel made with covered electrodes and gas welds have been found to be as corrosion resistant as the base metal in such media as tap water, boiler feed water, gasoline, sea water, salt spray, organic acids, mineral acids, alkalies, petroleum vapors, marine, rural and industrial atmospheres and underground. Arc welds with bare electrodes are generally inferior in corrosion resistance.

Carbon arc welds in mild steel made under a shielding gas have better general corrosion resistance than carbon arc welds not so shielded.

Tests of good forge welds have indicated that the welds are equal to the base metal in resistance to corrosion.

In general welds in mild steel made by submerged arc welding resist corrosion equally as well as the base metal.

Flash and spot welds have demonstrated satisfactory resistance to corrosion.

Spot Welding of Steel with Protective Coatings.—The following notes are based on results of an investigation of the spot welding of steel carrying different protective coatings.

1. Spot welds made through phosphate coatings were subject to corrosion by salt spray.
2. Blackened (oxidized) surfaces could not be spot welded readily.
3. Spot welds made through electrically deposited tinning caused reduction

in corrosion resistance in the vicinity of the welds.

4. Spot welds made through electro-galvanizing, hot dip galvanizing and sherardizing were satisfactory from the standpoint of corrosion resistance.

Braze-Welded Joints.—Mild steel and cast iron are frequently gas welded with bronze rods and electrolytic action or preferential corrosion on either the weld or base metal by the media in which mild steel and cast iron are ordinarily used is not generally observed. Welds in cast iron made with mild steel electrodes will suffer accelerated corrosion in some environments such as salt water. Cast-iron braze-welded specimens resist corrosion in sea water and in most corrosive soils.

Oxygen-Cut Surfaces.—In most instances oxygen-cut surfaces in mild steel have better corrosion resistance than planed surfaces.

Welds at Elevated Temperatures.—Welds in mild or low-alloy steel, when of approximately the same composition as the base metal, have been as satisfactory as the base metal in resistance to corrosion at elevated temperatures.

Welds vs. Rivets.—Whatever difference there may be between the corrosion resistance of riveted and welded joints appears to be in favor of the welded joint. Caustic embrittlement is not ordinarily encountered in good quality butt welds except where the environment includes a concentrated alkali and the welding stresses have not been relieved by appropriate heat treatment.

Electrochemical Potential.—Differences are very small in the electrolytic potential between good quality steel weld metal and its adjoining mild steel base metal, and so electrolytic action between such welds and base metal, is unlikely to result in serious attack by corrosion. So long as the weld metal is more noble than the base metal even large differences in composition between base metal and weld metal may not lead to local corrosive attack as, for example, in the case of austenitic welds in mild steel, or bronze welds in mild steel or cast iron.

Low-Alloy Steel

Low-alloy steel base metal or weld metal containing chromium, copper or nickel has somewhat greater resistance to corrosion than plain mild steel. In general, well-reinforced welds of good quality in low-alloy steels made by either arc or gas welding will give the same length of service under corrosion as the base metal. Welds made with low-alloy steel filler metal in carbon steel plates will be given some cathodic protection by the plates and will resist corrosion well. Carbon steel welds in low-alloy steel plates may suffer accelerated corrosion and are less desirable than welds made with alloy steel filler metal for use with alloy steel plates.

Galvanized Steel

Arc and gas welds made with steel filler metal in galvanized steel require some protective coating if they are to equal the galvanized steel in resistance to corrosion. The zinc coating on either side of the weld and on the underside of single-vee groove welds is damaged so that the corrosion resistance of the steel is low at these points. Gas welds made with bronze rods are not attacked in the service for which galvanized steel is ordinarily used but the zinc coating adjoining the weld is damaged to some extent. The corrosion resistance of galvanized iron acetylene generators, with braze welded joints, has been satisfactory. Usually some inhibitor against rusting is added to the water in the generator.

Stainless Steel

Stainless steels, designed primarily for corrosion resistance, may be grouped as follows:

Plain chromium steels containing from 12–25% chromium.

Austenitic steels containing approximately 17–25% chromium and 7–25% nickel. (In some austenitic steels various amounts of the nickel may be replaced by manganese.)

The corrosion resistance of these steels is attributed to the formation of a passive film or oxide on the surface. In general, the resistance to corrosion increases with the chromium content and the resistance to the non-oxidizing type of corrosion is markedly increased by the addition of nickel. The corrosion resistance of austenitic steels is further enhanced in a considerable number of media by the addition of molybdenum.

Satisfactory arc and gas welds with corrosion resistance approximating that of the base metal can be obtained in all

of these steels. Stainless steels, generally of the austenitic type, can also successfully resist corrosion when welded by flash, spot and seam welding. Welded vessels of stainless-clad steel are used extensively in a variety of corrosive media. Steel equipment is often protected by liners consisting of thin sheets welded in place to provide a complete covering. Chapter 37A contains more detailed information on the welding of these steels.

In most instances a given stainless steel is welded with filler metal that will give weld metal of approximately the same composition as the base metal. If, however, for some reason filler metal of a different composition is used, care must be exercised to insure that the weld metal is at least as corrosion resistant as the base metal. The welding of these steels presents some difficulties not ordinarily met with in working with mild steels. For example, the corrosion resistance is adversely affected by increase of carbon, so generally an effort is made to maintain the carbon content under 0.08% in both the weld and base metals.

The straight chromium steels in the as-welded condition are subject to loss of ductility of the weld, and in some media the areas adjacent to the welds are less resistant to corrosion than the unaffected base metal. Heat treatment after welding, at 1350 to 1600°F. (732 to 870°C.) for a few hours restores the corrosion resistance and makes some improvement in the physical properties.

The austenitic steels of the 18–8, 25–12, 25–20 chromium-nickel types in the as-welded condition are subject to intergranular corrosion or *weld decay* in the base metal adjacent to the weld, and this condition is still more marked in the case of structures in which two or more welds intersect. This condition may be corrected by heat treatment at 1950°F. (1066°C.) or higher. It is prevented by the use of columbium or titanium in the base metal and of columbium in the weld metal. In most instances the carbon content is maintained at 0.08% maximum with a titanium to carbon ratio of 4:1 to 5:1 or with a columbium to carbon ratio of from 6:1 to 10:1, depending upon the requirements of the service. Susceptibility to weld decay can be avoided also by restricting the carbon content of the steel to 0.03% maximum.

The addition of molybdenum for improvement in general corrosion resistance of the base metal does not eliminate weld decay (intergranular corrosion). The elements molybdenum and columbium are ferrite formers that tend to unbalance the austenitic structure of the 18–8 chromium-nickel steels with consequent lowering of corrosion resistance in some media, but the correct balance can be maintained by increase of nickel content in the steels containing molybdenum or columbium or both. Only as much molybdenum is used as is required by the service, and the nickel content in both base metal and weld metal is increased to 12–14% or the weld metal may be as high as 15–25%.

Somewhat higher chromium and nickel contents are often employed in filler metal than in the base metal to offset the loss of chromium that occurs when the metal is melted, and to insure that enough nickel is present to give adequately austenitic weld metal.

Residual stresses associated with the welding of stainless steels may make them subject to stress corrosion cracking in a very few specific media. This difficulty can be overcome by applying appropriate stress-relief heat treatment to alloys so constituted that they will not be rendered susceptible to intergranular corrosion by the stress-relief treatment or by the use of an annealing treatment.

Corrosion (Oxidation and Scaling) of Welds at Elevated Temperatures.—Heat-resisting alloys of the chromium-iron (Cr 5–30%), the chromium-nickel (Cr 20–30%, Ni 3–30%), and the nickel-chromium (Cr 8–20%, Ni 35–80%) types are being welded for high temperature service by gas and arc welding.

When gas welding the straight chromium and the low-nickel, high-chromium alloys, a neutral flame should be employed in order to preserve maximum corrosion resistance in the weld metal. The high-nickel, low-chromium alloys require a neutral or slightly reducing atmosphere.

Filler metal for both gas and arc welding should be of the same composition as the material being welded, except that they should preferably have a little higher chromium content to allow for chromium depletion during welding.

Effects of the heating during the welding operation may impair oxidation resistance as well as liquid corrosion resistance. The inclusion of stabilizing elements will be effective in overcoming em-

brittlement of the weld and base metal in structures required to operate in adverse temperature ranges. Restricting the carbon content to 0.03% max. or even 0.02% max. for the most severe conditions is also helpful although this results in a slight reduction in the tensile strength at elevated temperatures.

It is imperative that all the flux be removed from all welded areas before the parts are placed in high-temperature service; otherwise a slagging action occurs that promotes rapid destruction of the alloy.

Nickel and Alloys

Nickel, Monel and Inconel.—Filler metal of substantially the same composition as the base metal is used so that welds will have the same corrosion-resisting properties as the base metal. Best performance is assured by the selection of the proper filler metal and the use of the proper technique for depositing weld metal so as to produce sound welds and avoid such defects as gas pockets, laps, undercutting and excessive slag inclusions. Residual flux should be removed.

Tests and experience have established that welds possessing satisfactory corrosion resistance can be made with nickel, Monel, and Inconel by gas, arc and resistance welding, the choice of process being determined generally by factors other than corrosion-resistance requirements. (Chapter 35 contains more detailed information on the welding of nickel and its alloys.)

Welds in nickel, Monel and Inconel-clad steel are made preferably by the metal-arc process, using electrodes of appropriate composition. The recommended procedures minimize dilution of welds by iron from the base metal. Experience has shown that in the services for which these clad metals are used, properly made welds demonstrate adequate corrosion resistance. In case of Inconel-clad steel, there has been some use of the more highly alloyed 80% nickel, 20% chromium alloy filler metal in order to compensate for iron dilution of the welds.

Satisfactory corrosion-resistant welds can be made with all the Hastelloy compositions. Castings of Hastelloy grades A, B and C can be welded best by the gas welding, atomic hydrogen or inert-gas metal-arc welding processes. Welding should be followed by full annealing to preserve corrosion resistance.

Wrought Hastelloys are generally welded by the shielded metal-arc process though gas, atomic hydrogen, inert-arc and submerged arc welding processes also have been applied successfully. Hastelloy A should be heat treated followed by rapid air cooling from 2100 to 2150°F. after welding in order to preserve corrosion resistance. Similar treatment is desirable for Hastelloys B and C where the service conditions are severe except that the annealing temperature for Hastelloy C is 2200 to 2250°F.

Hastelloy D castings should be preheated to about 1400°F. before welding and should be kept at an even temperature during welding and then allowed to cool slowly to 800°F. Hastelloy D castings should be preheated to about 1400°F. before welding and should be kept at an even temperature during welding and then allowed to cool slowly to 300°F.

Satisfactory corrosion-resisting welds may be made with either cast or wrought Illium, using rod of the same composition. Both metal arc and gas welding are used. In gas welding, a reducing flame is preferred.

Aluminum and Its Alloys

General.—The resistance to corrosion of many of the aluminum alloys is not reduced by welding. The high strength heat-treatable alloys may be adversely affected by welding, but these adverse effects can be largely corrected by heat treatment after welding. Clad products of these and other alloys are much less affected by welding and are preferred where corrosion is a factor. The resistance to corrosion is dependent more on the alloys used than on the nature of the welding operation.

Effect of Alloy.—The following are the different types of aluminum alloys whose corrosion resistance is not appreciably affected by welding. Commercial alloys of the several classes are included as examples. High purity aluminum and commercially pure aluminum (2S); aluminum-manganese alloys (3S); aluminum-manganese-magnesium alloys (4S); aluminum - magnesium - chromium alloys (52S); aluminum-magnesium silicide alloys (53S, 61S, 63S, R353, R361); aluminum-silicon alloys (cast alloys 43, 356). These alloys or clad products of them, such

as Alclad 3S and Alclad 4S, generally exhibit a good inherent resistance to corrosion. Combinations of these alloys also have good resistance to corrosion. Consequently, where corrosion is an important factor, the aluminum alloys used should be chosen from these materials.

The aluminum-copper alloys, that is those with substantial amounts of copper such as 14S, 17S and 24S, usually have their inherent resistance to corrosion lowered by welding. The resistance to corrosion of 14S-T6, 24S-T6 and 24S-T8 (because of artificial aging) is less affected by welding than is that of 14S-T4, 17S-T4 and 24S-T4 (naturally aged), and these former alloys could be considered for certain applications, especially if service conditions are mild. Painting to protect the metal is effective in preventing attack as long as the paint coatings are adequately serviced. It is important that alloys 14S-T4, 17S-T4 and 24S-T4 be heat treated after welding to provide a resistance to corrosion comparable to that of the base metal. This also effects an increase in strength.

Welded Alclad products will exhibit a higher resistance to corrosion than the corresponding non-clad alloys similarly welded. This results from the electrochemical protection of the core alloy and the welded zone by the more anodic cladding. Commercially available alloys of this type are Alclad 3S and Alclad 4S. Alloys of Alclad 14S, Alclad 24S, Alclad 75S and R301 must be classed as experimental for either gas or arc welding as little experience or service information exists. Some exposure testing indicates that these latter four alloys in the as-welded condition may not resist corrosion as well as the unwelded Alclad material. Considerable improvement is obtained by heat treatment after welding; therefore, when practicable and when optimum resistance to corrosion is required, the assemblies should be heat treated and artificially aged, if required, after welding.

Commonly used filler metal are commercially pure aluminum (2S), aluminum-silicon alloys (43S) and aluminum-silicon-magnesium alloy (356). These alloys have a good inherent resistance to corrosion. For maximum resistance to corrosion, especially to certain chemicals, commercially pure aluminum or high purity aluminum is preferred. Aluminum filler metal with substantial amounts of copper are not as resistant to corrosion as those mentioned previously. They may produce stronger welds, however, and frequently have adequate resistance to corrosion for specific applications where service conditions are mild. Most aluminum alloys, however, are anodic to welds containing substantial amounts of copper and tend to electrochemically protect them, especially in the presence of good electrolytes, such as salt water.

Effect of Welding Process.—Gas welding, carbon-arc welding, metal-arc welding, inert-gas metal-arc welding and atomic hydrogen welding generally result in only minor differences in the resistance to corrosion of the weld and base metal. Consequently, the welding process is usually chosen on the basis of factors other than resistance to corrosion, with one exception. Inert-gas metal-arc welding does not require the use of a welding flux; this eliminates corrosion hazards resulting from incomplete removal of fluxes.

Three common types of brazing are used: torch, furnace and dip. Their specialized nature limits the alloys generally used. Brazed joints resist corrosion in a manner similar to that of like combinations of alloys when arc or gas welded. The base metal is usually commercially pure aluminum, aluminum-manganese alloy or aluminum-magnesium silicide alloys. When used with aluminum-silicon alloy cladding or filler metal, a resistance to corrosion comparable to that of the base metal results. Aluminum-silicon-copper filler metal produces a joint of somewhat lower resistance to corrosion. This combination, however, can be used successfully in many corrosive environments of mild to moderate severity. Generally the brazing metal is electrolytically protected by the adjacent alloy.

Spot, seam and flash welding do not alter significantly the resistance to corrosion of most of the aluminum alloys. Among the alloys not affected are alloys 2S, 3S, 4S, 52S, 61S, 63S, R353 and R361. Spot welds in Alclad products such as Alclad 3S, Alclad 4S, Alclad 24S-T4, Alclad 14S-T4, Alclad 14S-T6, Alclad 75S-T6 and R301 are electrochemically protected by the cladding on the sheet, even if the weld extends through the cladding. However, maximum resistance to corrosion is obtained when the weld does not extend through the cladding. Re-

sistance welding of dissimilar aluminum alloys in the preceding group generally has only minor effects on the corrosion resistance of the composite assembly.

Resistance welds in 14S, 17S, 24S and 75S aluminum alloys may be selectively attacked under severe or moderately severe conditions. For this reason, spot-welded construction of these latter alloys is to be avoided where corrosion is a factor. When 14S, 17S, 24S, and 75S are resistance welded to cladded forms of these alloys or to R301, the claddings generally will electrochemically protect the unclad material and the spot welds at the faying surface. Consequently, an improved resistance to corrosion of the joint results.

Flux Residues.—The fluxes used to weld or braze aluminum alloys are corrosive and it is important that the residues be completely removed; otherwise, they will cause appreciable corrosion, especially under humid conditions or sheltered conditions where there is little opportunity for the flux to be washed away. Flux residues also cause early failure of paint coatings. Several effective flux removal treatments are available.

Environment.—The characteristics of aluminum alloys described above are based largely on performance when exposed to natural corrosive environments, such as inland and seacoast atmospheres, sea water, fresh waters and soil. Exposure to certain chemicals or chemical processes might alter or even greatly exaggerate minor differences resulting from welding and combinations of dissimilar metals used. Such factors should be evaluated in terms of the specific corrosive environment involved.

See Chapter 32 for further information on aluminum and aluminum alloys.

Magnesium and Its Alloys

Magnesium and all of the commercial magnesium alloys are weldable. The welding processes most widely used are inert-gas metal-arc welding, gas welding and spot welding. Other joining processes in use are brazing and soldering. (Chapter 33 contains more detailed information on the welding of magnesium and its alloys.)

Since all arc-welded joints are made only with the inert-gas metal-arc process, no flux is used and the joints require no special cleaning. Under normal conditions of exposure the joints are as resistant to corrosion as the base metal. In certain chemical solutions, particularly chloride solutions, pitting adjacent to the weld in the heat-affected zone may develop. Filler metal of different composition from the base metal does not cause galvanic attacks when used as recommended.

Service experience has shown that spot-welded joints of magnesium alloys have as good corrosion resistance as the base metal, provided that copper pickup is avoided by keeping the electrode tips clean. Copper pickup can be removed by abrading the surfaces of the spots. The faying surfaces of spot welds seldom require any special protection. Sea coast exposure tests over a period of four years at Kure Beach, N.C., showed only a thin magnesium hydroxide film at the interfaces. For very severe exposure conditions, special wet sealing paints may be applied to the interfaces just prior to spot welding.

Highly corrosive fluxes are used in the gas welding of magnesium and its alloys. Therefore, only simple butt joints from which flux can be easily removed are recommended. Directions for cleaning gas welded joints are given in Chapter 33. Joints that have been properly cleaned of residual flux exhibit as good resistance to corrosion as the base metal. As in arc welds, selective attack in the heat-affected zone may occur in specific chemical solutions.

Magnesium alloy M1 can be brazed using fluxes similar in composition to the gas-welding fluxes. The same precautions of complete removal of flux residues from the brazed joints must be observed as with gas-welded joints. Complete removal of residual flux from brazed joints is more difficult than in gas-welded joints because the lap joint is widely used. Therefore flux removal becomes a more important consideration than in gas welding.

Magnesium alloys containing aluminum and zinc, such as AZ31X and others of higher alloy content, are subject to stress corrosion cracking if left in the as-welded condition. The stress corrosion cracking is completely eliminated by giving the welded parts a low-temperature stress relief as described in Chapter 33.

Copper and Its Alloys

Copper.—Gas welding, preferably of deoxidized copper, using rod of the same composition, or alloyed so as to lower the melting point slightly, is practiced most commonly, and produces welds that demonstrate satisfactory corrosion resistance. Similarly good results are obtained from carbon-arc welds using silicon bronze or phosphor bronze rods which deposit weld metal that has adequate corrosion resistance without introducing complicating galvanic effects in the usual applications.

The use of high zinc (40%) brasses for brazing copper may lead occasionally to corrosion difficulties in environments in which the brass itself is vulnerable to attack which will be accelerated by the surrounding copper. Silver brazed joints in copper are considered satisfactorily corrosion resistant.

Brasses and Bronzes.—Common brasses are gas welded or brazed with high zinc (40%) filler metal and low brasses or phosphor bronzes may be similarly joined for uses where corrosive conditions are mild. For more severe corrosive conditions, low brasses and bronzes should be joined by brazing with a silver alloy or carbon-arc welding with phosphor bronze welding rod in preference to brazing with high-zinc brass. The silicon bronzes which are adapted to either gas or arc welding also may be used for joining copper and high copper alloys where corrosive conditions are severe. Silicon bronze welding rods are, of course, particularly suitable for joining silicon bronzes of the same composition.

The silicon bronzes are particularly well adapted to welding by gas or arc welding using filler metal of the same composition, which yields deposits possessing corrosion resistance equal to that of the base metal.

Chapter 34 contains more detailed information on the welding of copper and its alloys.

Lead and Its Alloys

Gas- or resistance-welded lead joints are generally equal to the base metal in resisting strong chemical solutions. Welded joints in lead-base alloys are also usually as resistant to attack as the base metal. Occasionally some selective attack at the weld occurs as a result of the inclusion of dross from the filler rod or of corrosion products from the sheets being welded. See Chapter 36 for more detailed information on the welding of lead.

BIBLIOGRAPHY

Impact Resistance

1. *Effect of Certain Factors on the Izod Value of Weld Metal,* L. W. Schuster, The Welding Journal Res. Suppl., November 1939.
2. *Weldability—Cracks and Brittleness Under External Load—Part III—Tests for Cracking Under External Load—Impact and Tensile Tests—A Review of the Literature to July 1, 1939,* W. Spraragen and G. E. Claussen, The Welding Journal Res. Suppl., November 1941.
3. *Behavior of Spot Welds Under Impact,* A. M. Unger, H. A. Matis and E. P. Gruca, The Welding Journal Res. Suppl., February 1942.
4. *The Effect of Speed of Loading Upon the Ductility of Steel Structural Members,* W. M. Wilson, The Welding Journal Res. Suppl., July 1943.
5. *Impact and Tensile Properties of Pulsation Spot Welds,* A. S. Gelman, The Welding Journal Res. Suppl., March 1944.
6. *The Dynamic Properties of Flash-Welded Tubing,* R. B. Bland and P. E. Sandorff, The Welding Journal Res. Suppl., June 1944.
7. *Effect of Notching on Strained Metals,* G. Sachs and J. Lubahn, The Welding Journal Res. Suppl., June 1944.
8. *Impact Strength of Arc Welded Joints in Aircraft Steel,* H. O. Klinke, The Welding Journal Res. Suppl., December 1944.
9. *The Impact Strength of Some Metallic Arc Welding Metal Deposits at Elevated Temperature,* J. F. Eckel and R. J. Raudebaugh, The Welding Journal Res. Suppl., July 1945.
10. *Improvement of the Notch Impact Resistance of Gas-Welded Joints,* A. Matting and H. Koch, The Welding Journal Res. Suppl., June 1946.
11. *An Investigation of Beams with Butt-Welded Splices Under Impact—Part I—Impact and Static Tests on Beams Including Preliminary Studies of the Resistance to Impact at Sub-Zero Temperatures,* W. J. Krefeld and E. C. Ingalls, The Welding Journal Res. Suppl., July 1947.
12. *Report on the Fracture of Metals—Part I,* M. Gensamer, Edward Saibel and J. T. Ransom, The Welding Journal Res. Suppl., August 1947.

Fatigue Resistance

1. *Fatigue Tests of Riveted Joints,* Engineering Experiment Station, University of Illinois Bulletin 302, May 31, 1938.
2. *Fatigue Tests of Welded Joints in Structural Steel Plates,* Engineering Experiment Station, University of Illinois Bulletin 327, February 25, 1941.
3. *Fatigue Tests of Commercial Butt Welds in Structural Steel Plates,* Engineering Experiment Station, University of Illinois Bulletin 344, October 12, 1943.
4. *Fatigue Strength of Fillet Weld and Plug Weld Connections in Steel Structural Members,* Engineering Experiment Station, University of Illinois Bulletin 350, March 14, 1944.

CHAPTER 41

FACTORS AND DATA INVOLVED IN ESTIMATING COSTS*

INTRODUCTION

THE COST INCIDENT to the use of any welding process is a consideration of great importance to the user of welding. This chapter is devoted to a presentation and discussion of various cost factors in welding processes; the use of these data must naturally involve a careful analysis of the particular application and the circumstances in which a given process will be used.

This chapter covers the following processes:

Manual Metal Arc Welding
Atomic Hydrogen Arc Welding
Carbon-Arc Welding
Submerged Arc Welding
Manual Oxy-acetylene Welding

Data covering welding processes other than those listed above are included in those chapters of the HANDBOOK relating to the processes.

IMPORTANT GENERAL FACTORS INFLUENCING WELDING COSTS

The choice of a welding process for fabricating a given product is influenced by several factors, all of which should be thoroughly considered before the final selection is made.

An important general factor is the desirability of keeping a welding organization continuously at work without slack periods. It is sometimes desirable to manufacture side line equipment which can be produced in any slack periods between the production of the main product. Such a plan keeps a shop in full operating strength for its main business and provides constant employment and broader experience for its personnel.

In addition, many other less general factors may affect the cost of welded products. The following are considered especially important and are so general that they should apply to almost any welded construction, whether arc welded, gas welded or brazed.

They are as follows:

1. Design to reduce the amount of weld metal required in the structures.
2. Plan to utilize material most effectively.
3. Use setting-up fixtures to eliminate measuring, to standardize structures and to facilitate fit-up.
4. Use fixtures to position joints for making welds in most favorable positions.
5. Use the most economical size and type of filler metal.
6. Obtain a good operator factor (use of workman's time).

A detailed discussion of each of the six factors follows.

Design to Reduce Welding and Deposited Weld Metal

As soon as an organization has committed itself to produce a certain type of structure or equipment by welding, a careful analysis of the design of the unit to reduce the amount of necessary welding often yields important economic advantages. *Fundamentally, weld metal is expensive; and all other factors being equal, the welded design with the least weld metal is the most economical.*

Examples of eliminating welding in the design of the structure include fabricating bridges from large rolled I-beams rather than from built-up welded structures, or making of parts for weldments from

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plates or other rolled steel products or by extrusion.

The use of rolled shapes instead of built-up members and the placing of welds at points of least cross-section or least load in the member, all tend to reduce weld metal deposition and, therefore, costs.

The design of structures to place welds in the most accessible locations and in the most favorable positions, and the use of bolted field connections often reduce costs.

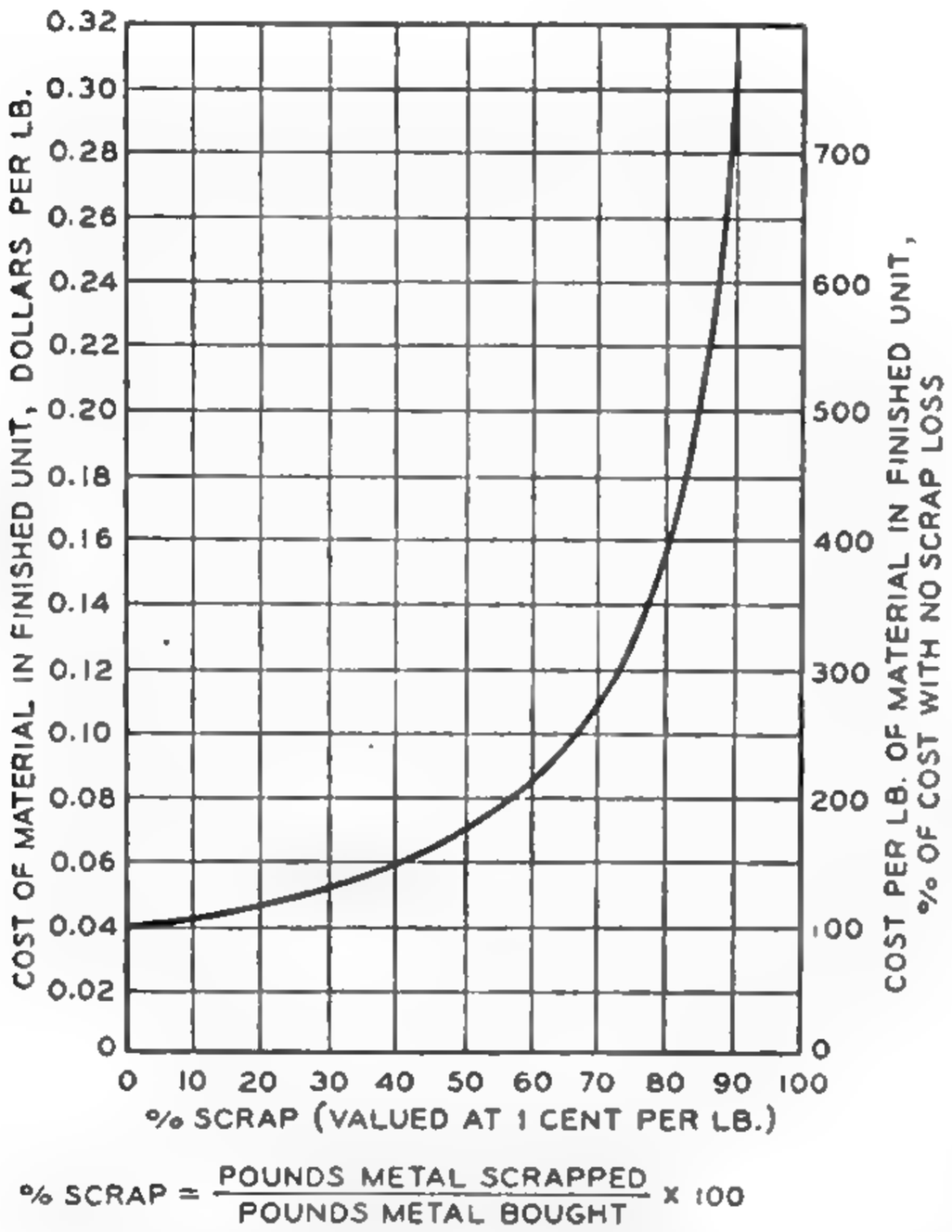


Fig. 1.—Relationship Between Cost of Scrap and Total Material Cost

Material should preferably be of thicknesses which can be readily handled with available equipment. Built-up sections of thin material which require less weld metal to join and which give deep sections to carry stress are often more economical than thick sections.

Except where heavy weight is desirable, the minimum material necessary for the structure should be used. Under a bending load, a built-up member can weigh less than a rolled member, because the built-up section of the welded member can be made to conform to the moment curve.

The design should be planned to use the minimum amount of weld metal by use of narrow welding grooves, small continuous fillet welds rather than larger intermittent fillet welds and the location of welds where the strength will be utilized most effectively. The same type of welds should be used as widely as possible so that not too many welding procedures will be required.

Plan to Utilize Material Effectively

While steel is a relatively inexpensive material, there is enough margin between its economic use and waste to make planning to minimize scrap worth while. This is especially true where shapes are cut in large quantities from bars, sheet, strip or plate.

Careful forethought should be exercised in designing the parts for welded structures, so they can be taken from the raw material economically. Small parts should be designed to be made from left-over pieces. Wherever possible the original cut should also serve as the edge preparation. Figure 1 graphically illustrates the rise in the cost of material for welded structures with the increase in the percentage of scrap material. Normally at least three-quarters of the original value of a pound of material is lost when it becomes scrap. This cost must be added to the cost of the actual material used.

Use Setting-up Fixtures

Any method of mass production which is sound must produce a standardized finished product. One of the most important aids to standardized welded products is a fixture for setting up the component parts of the structure prior to welding.

This setting-up operation must be accurately done, yet it may be done with a widely varying amount of measuring and attention, resultant setting-up costs varying accordingly.

Good welding practice dictates that for a repetitive operation, there should be setting-up fixtures which allow an operator to place the component parts of a structure in the fixture without error, and in their proper relationship. This should be done with a very minimum of measuring of individual parts and without careful positioning.

A fixture provides stops (a framework upon which to place the parts) and plugs, guards and clamps which accommodate pre-machined or other parts in their

proper relationship. It reduces setting-up time to a bare minimum and provides maximum standardization of the structures.

Stop-watch studies of setting-up operations with and without fixtures indicate differences of several hundred percent in setting up without a fixture compared to setting up with a good fixture. This is mostly due to the additional measuring and fastening time required without a fixture.

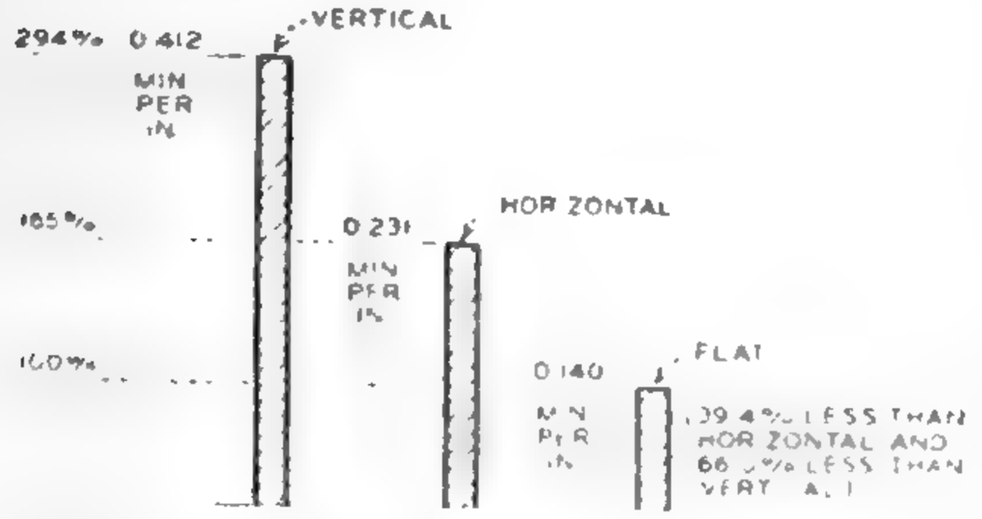


Fig. 2.—Relative Speeds and Costs for 3/8-In. Fillet Welds in Different Positions

Use Positioning Fixtures

The use of positioning equipment results in lower costs where the welds are of sufficient size and length and the work is of such a nature that it can be positioned. In general, single-pass fillet welds up to and including 5/16 in. can be made more economically in the horizontal position on weldments requiring cranes to position. For larger fillets lower cost and improved appearance are usually obtained by positioning the work. Positioning will permit the use of the larger diameters of Class E6020 and similar types of electrode, with higher deposition rates.

Because weld metal is liquid at the time it is deposited, the position of the joint at the time in which a weld is deposited automatically establishes certain limitations on the size of the electrode and the amount of the molten metal which can be deposited within a certain time on a joint. Ordinarily the nearer a weld may be deposited in the flat position, the less is the difficulty encountered due to the fluidity of the metal, and within certain limits, the larger the welding electrode which may be used. This is especially true of thick plates although it applies to even relatively thin plates.

There are many types of jigs or positioning fixtures for placing welds in the best position for welding. They may or may not be power-driven, mechanical positioning fixtures, and there are many rather standardized and commercially available types. They may also be made by the manufacturer of the welded structure. It is frequently possible to combine setting-up fixtures with positioning devices into a single piece of equipment.

Figure 2 illustrates in graphic form the relative cost of depositing 3/8-in. fillet welds in the different positions—vertical, horizontal and flat. Actual time study values on which this figure is based include arc time plus fatigue allowance. The basis for the figures in this graph are numerous time studies of actual weld deposition time under normal shop conditions, using arc time and electrode changing time, and adding an appropriate allowance for operator fatigue (20% of total time).

Because of gravity the horizontal leg of a fillet weld made in the horizontal position tends to be longer than the vertical leg. Consequently, if the vertical leg is made of the specified size, there is often a degree of overwelding which appreciably increases the welding cost.

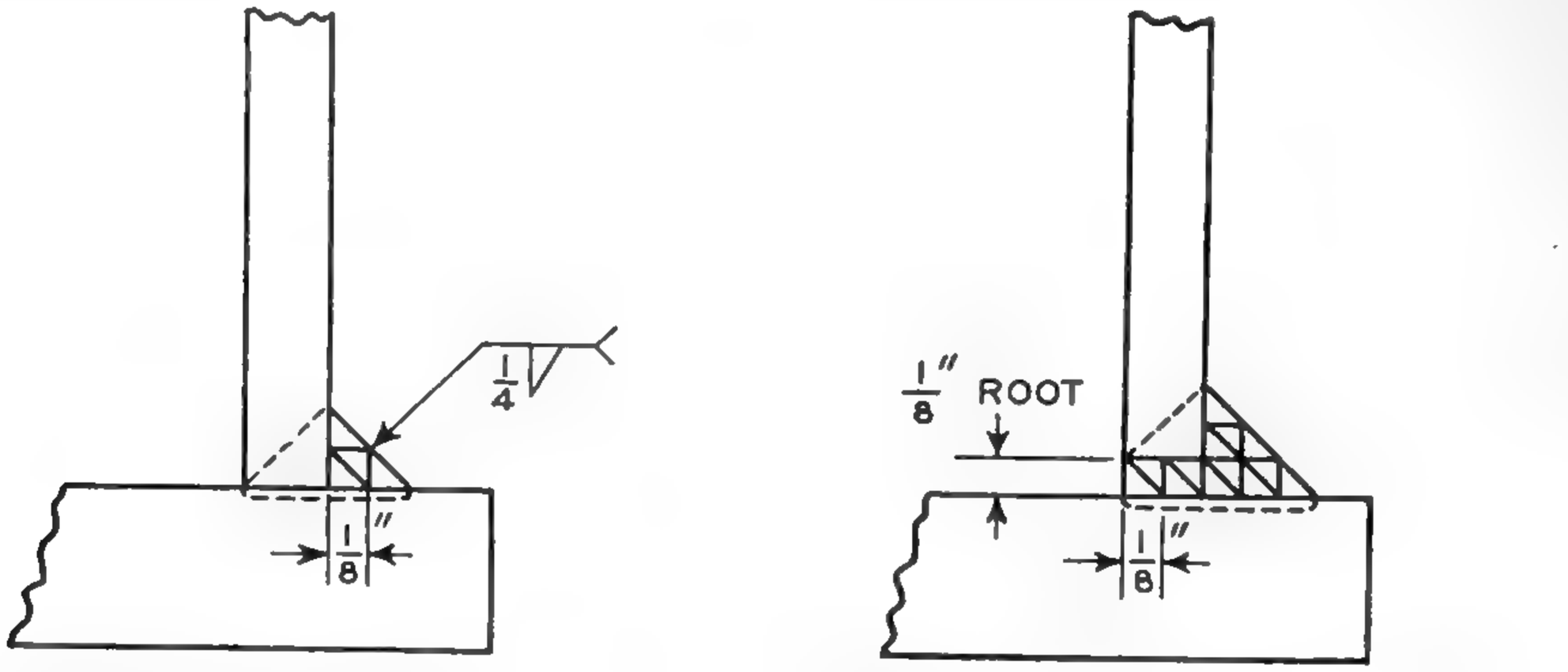
Figure 3 shows the volume of a weld such as might be found in a fillet joint compared to the volume of the same weld made with a gap in the joint equivalent to one-half the size of the weld, followed by the normal practice of the operator of applying an additional amount of weld metal to be sure that the weld is sufficiently strong.

Figure 4 shows the additional metal used to weld a poor-fitting butt joint. Approaching the economics of this problem from the volume of weld metal alone, comparison shows that a filled gap one-half the thickness of the plate plus the additional amount placed by a conservative operator for safety, represents from two to three times the amount of weld metal used in the joint when it is a normal fitting joint.

This comparison leads to a vast understatement of the cost of a poor-fitting joint because in the gap-filling process an electrode much smaller than is normal is required and a much longer time than usual is required for cleaning after each successive welding pass and for cooling

of the joint between passes. This greatly increases the time of deposition over what would normally be used with the regular size electrode for a normal joint. A poor-fitting joint almost invariably costs from two to four or five times what the same joint would cost if properly fitted. The use of setting-up fixtures will greatly reduce poor fit-up.

Stop-watch studies of burn-off rates of welding electrodes of different sizes from $^1/_8$ to $^5/_{16}$-in. diam. and all of the same length indicate that, with the proper machine setting for the deposition of an electrode on an average job, each takes about the same length of time. This time varies somewhat, but usually it requires about 75 sec. arc time to melt 12



GOOD FIT-UP (4-1/8 TRIANGLE VOLUMES USED) —VS.— ROOT OPENING 1/2 THE SIZE OF WELD (9 TRIANGLE VOLUMES REQUIRED AND 13 PROBABLY USED)

Fig. 3.—Graphic Illustration of Cost of Poor Fit-Up in Fillet Welds

Use the Most Economical Size and Type of Filler Metal

The selection of the correct type of filler metal for a given application is important. The characteristics of the generally recognized types of filler metal are given in Chapter 38. Often the selection of the most suitable and least expensive type of filler metal depends upon some experimentation and an analysis of the purchase price of the electrodes considered.

Electrodes should be burned down to short stubs, usually $1^1/_2$ to 2 in. or less in length. To minimize spatter loss, the electrodes should be melted at the rate which yields the most pounds deposited per unit of time.

After the type of electrode has been determined the selection of the proper size for the application is a very important cost factor. The amount of weld metal deposited by a given size of electrode per unit of time depends more upon the volume of metal in the wire in the electrode than upon any other factor.

in. of electrode with a normal machine setting.

Assuming this value to be correct and assuming that the linear rate of melting electrodes of different diameters is the same, then the amount of deposited weld metal for a given size of electrode depends upon the volume of the wire; and the length of time required to deposit a pound of weld metal is proportional to the square of the diameter of the electrode.

This relationship, assuming 75 sec. melting time and 15 sec. for changing electrodes, forms the basis for the differ-

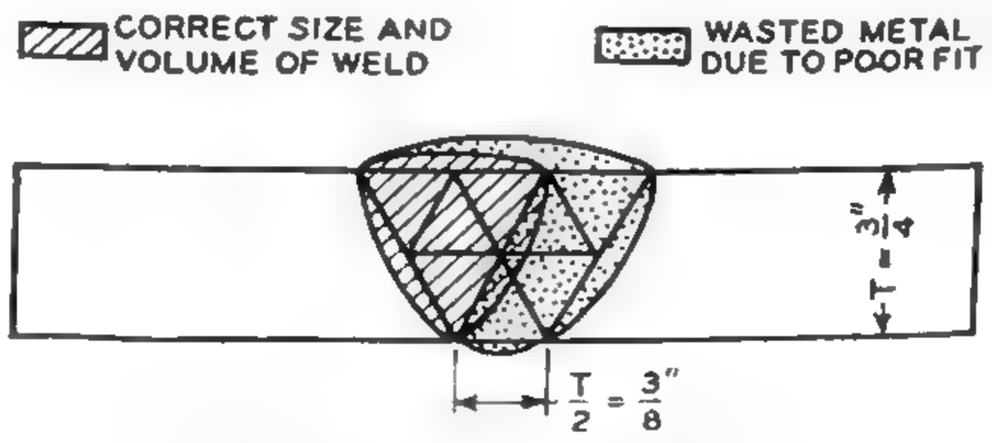


Fig. 4.—Graphic Illustration of Cost of Poor Fit-Up in Groove Welds

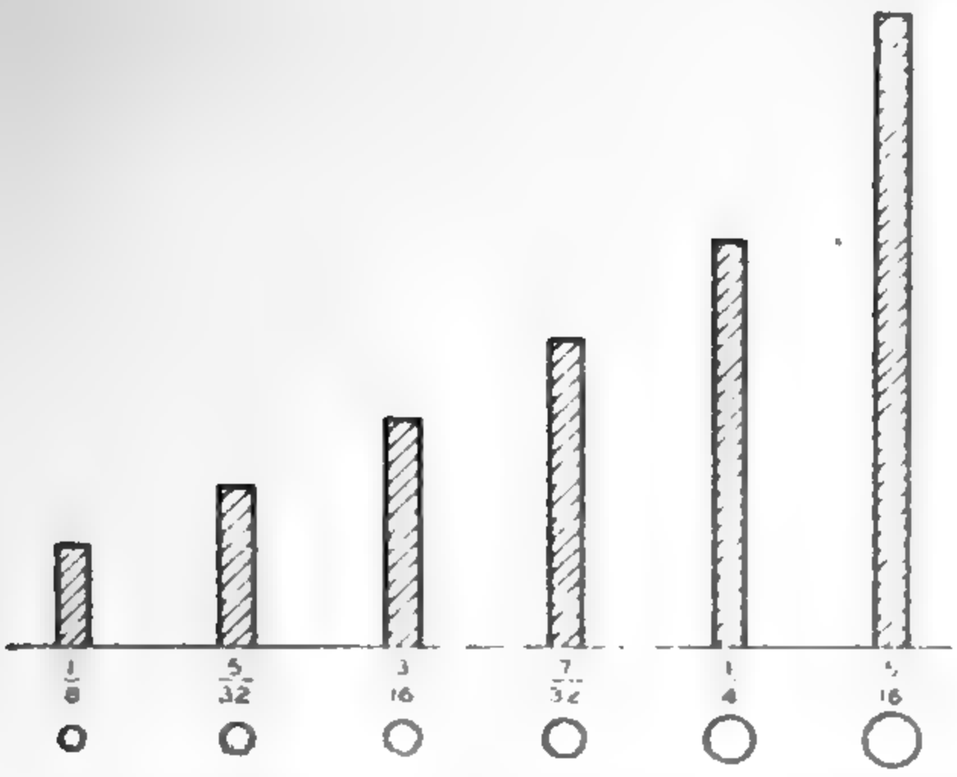


Fig. 5.—Relative Volumes of Metal Melted per Unit Time at Same Linear Rate from Electrodes of Different Diameters

ences in cost per lb. of deposited weld metal using different sizes of electrodes, assuming a constant cost per hour for labor.

Figure 5 shows the relative volumes of metal in 1/8, 5/32, 3/16, 7/32, 1/4 and 5/16-in. electrodes of equal length, based on their cross-sectional areas.

common practice and is very easily done, especially on structures which involve a large percentage of fillet type joints.

The comparison in Fig. 6 assumes that the specified 1/4-in. welds were increased only 50% from 1/4 to 3/8 in. The result is that *more than double the amount of weld metal is deposited.* Conservatively figured, it doubles the cost of the welding. This represents a 100% increase in the welding cost.

Obtain a Good Operator Factor (Use of Workman's Time)

A factor which exerts a far-reaching effect upon the total cost of a weldment is the operator factor. This is especially true of the welding operation itself, since it requires constant attention while the arc is maintained and since the percentage of arc time fundamentally controls the economy of the deposition of weld metal. If no arc exists, no weld metal is being deposited, no matter what the other conditions may be.

The same is true of cutting, bending,

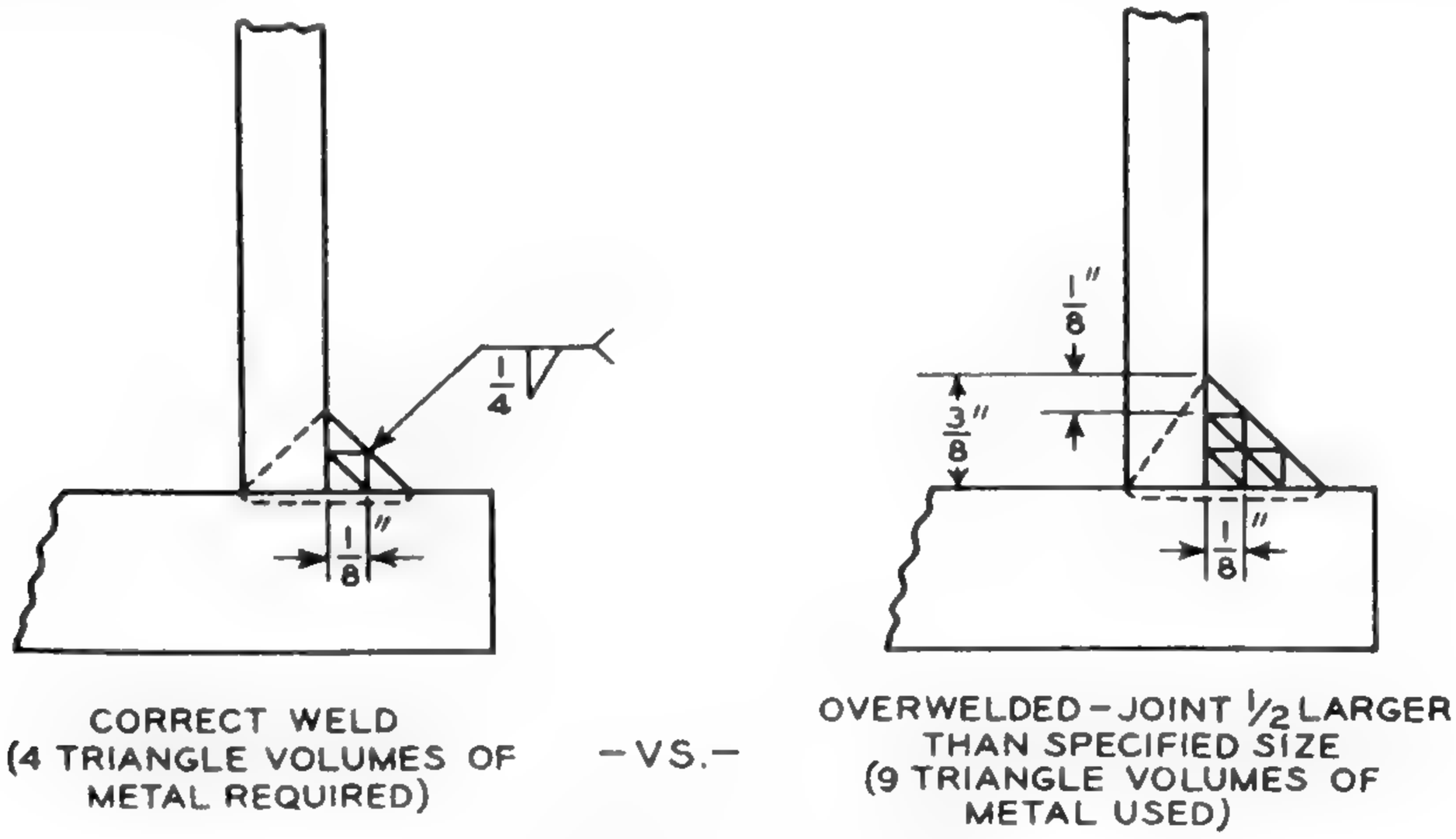


Fig. 6.—Effect of Overwelding

There are many times when smaller electrodes are used than should be. Even in some cases where positioning fixtures permit the use of welding electrodes of a size suitable for a given weld, smaller electrodes are used than are necessarily in keeping with good welding practice. This adds unnecessarily to the cost.

Overwelding.—Overwelding is a very

forming, machining, setting up and other direct labor operations, and the total effectiveness of the workman's use of his time on productive work greatly influences the total cost of the finished unit.

Welding labor costs usually include assembly and tack welding of the component parts as well as the actual welding, and incidental operations such as cleaning

slag from the weld and chipping the root or defects as required.

Whenever practicable, in order to arrive at accurate costs, assembly and tacking and any chipping should be segregated as individual items. In any event they should be considered as definite percentages of the total overall labor.

The actual welding time consists of arc or torch time, changing electrodes or welding rods, cleaning the weld, handling or positioning the work, moving about the work to be in the correct position to weld and personal allowances. The largest single factor of these is the arc or torch time, which for a given weld size with a given electrode or welding rod type and size, current and voltage or tip size and gas consumption can be very definitely controlled. All of the other factors will vary with the type of work but it is customary to establish them as certain allowable percentages of the actual welding time for definite classes of work.

Arc time, as a percentage of actual welding time, will vary from as low as 10 to as high as 75%, depending on the type of work and handling facilities. An average figure for moderately heavy and large work is approximately 50%. A high percentage of arc time is, in general, an indication of efficiency on the part of the welder, but not necessarily of low cost, since a high arc time percentage may be obtained with small diameters of electrode as compared to the large diameters, whereas the increased deposition rates of the latter may result in lower cost in spite of lower arc time. In general, greatest economy can be obtained by using the maximum diameter of electrode permissible for the work.

Fundamentally, obtaining a high operating factor is based upon good planning, good shop lay-out, good organization of the work, good operation (mechanical condition) of fixtures, jigs, machines, etc., combined with good morale on the part of the workmen themselves. Sometimes an incentive system contributes tremendously to the effectiveness of workmanship or operator factor.

One general principle should be kept in mind: after the designer has exhausted his wit, after materials have been selected and processed until they bear imprint of many minds and machines; then the job goes to the welders with very exacting demands. Their performance determines whether the finished structure will be of poor or good quality; their skill and care can overcome little faults and eliminate many time-consuming details and their failure can mean the failure of much work done by others. Therefore, every obstacle to the work of the welder should be removed or lessened until its ill effects are of no importance.

Adequate specifications for all welding operations, the sequence of manufacturing processes, clearly defined standards of quality and intelligent supervision should be provided. The welder's work should be planned to minimize physical strain and to insure maximum safety. Special attention should be given to provide sufficient lighting for the welder to see the work easily. Proper ventilation should keep smoke, excess heat and dust away, and shelter should be provided against wind and adverse weather. All such measures to sustain the general well-being of the welder result in increased efficiency.

Figure 7 shows an example of the relative importance of a good accomplishment factor (operator factor), namely 70%, and a poor accomplishment factor, namely 50%, as applied to a hypothetical welding operation costing a total of $100 with good practice.

The value 70% may appear low but assuming eight $^3/_{16}$ × 14-in. electrodes per lb. and 24 lb. melted per day, at 90 sec. melting time and 15 sec. electrode change for each electrode, this results in a total of 42 min. of actual arc time and electrode changes per hr. for 8 hr. or a total of 336 min. of actual welding.

Because of the confining and demanding nature of arc welding, it is not uncommon to consider a 20% fatigue or rest allowance factor (12 min. for rest for each 48 min. of arc time plus electrode changing time) which, when computed on the above basis of 336 min. per 8-hr. day, results in an additional total of 84 min. of rest allowance which should be added to the 336 min. devoted to welding work.

This amounts to a total of exactly 7 hr., leaving only 60 min. remaining in the day for handling time, job starting and stopping, cleaning up, changing jobs, getting electrodes, and adjusting the work, such as turning fixtures, preparing to weld, etc. Therefore, 70% is a very good operator factor although

it is sometimes possible to achieve a higher one under most favorable circumstances.

A 50% operator factor which produces only 30 min. instead of 42 min. of welding work per hr. represents a direct welding labor cost which is 40% higher than the direct welding labor cost for a 70% operator factor.

In the case shown in Fig. 7, this 40% increase in labor costs causes a 24% increase in the total cost of the production of the unit.

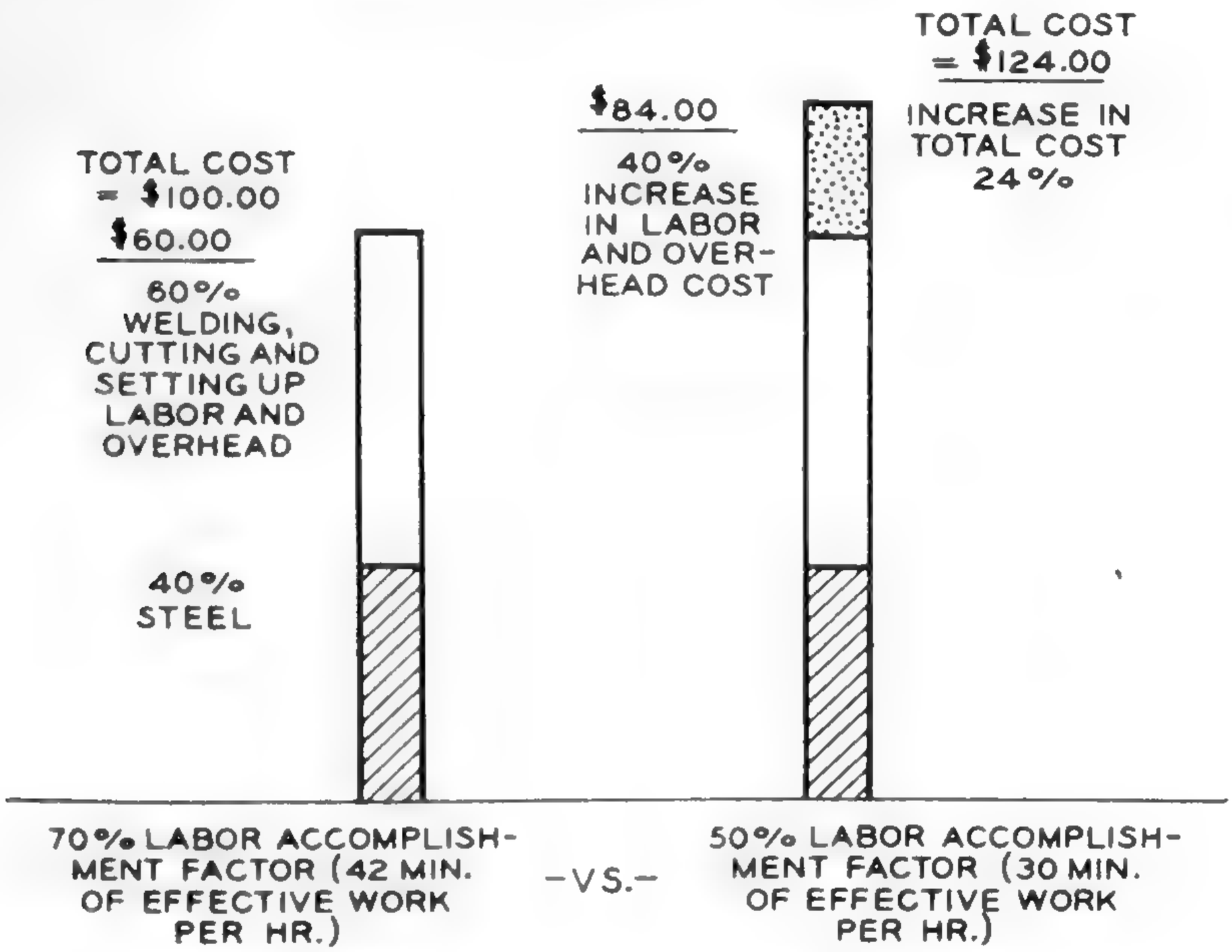


Fig. 7.—Effect of Labor Accomplishment on Total Cost

In the foregoing eight examples of the specific effect of a given factor on the cost of a welded unit, only one at a time has been considered. This has been done to make the relative value of each factor specific and pointed. It is important to show the cumulative effect on the total cost of all of the factors, all of which were relatively conservative in themselves, and compare them to the original cost based on normally attainable good practice.

Figure 8 shows the cumulative effect of all of these factors considered separately in a hypothetical example of a welded structure which requires $40 worth of materials and $60 worth of welding materials, labor and overhead in normally good practice, compared to the slightly poorer practices described and graphically shown in the illustration.

It should be borne in mind that each of these factors is considered separately in Fig. 8 without any special interrelation of the effects of one upon the other. For example, the cost of the effect of overwelding is based on the assumption that $^{1}/_{4}$-in. electrodes were used in good practice and will also be used in the overwelding. If a smaller electrode should be used, say $^{7}/_{32}$ in., which makes a difference of a total of $11^{1}/_{2}$% in the total cost of the unit, the cost of overwelding would be 27% greater than it actually was assumed to be. The same might be said of the consideration of the cost of welding with poor fit-up.

Even with this conservative approach, it is of considerable interest to observe that while assuming the almost ideal 70% operator factor, the total cost of the unit, with the accumulated cost effect of the less desirable practice (conservative though it may have been), amounts to $244.16. This is an increase of over 144%.

Should we assume a 50% operator factor instead of a 70% operator factor, the cost immediately goes to $322.82 or an increase of 222.8% above the cost of the normally attainable good practice, rated at 100%. Even if proper discount is made for the inclusion of elements which slightly increase the overhead in some of these costs, the accumulated cost of making these hypothetical units with the less desirable practice exceeds by 200% the cost with normally attainable good practice in arc-welding manufacture. often provide a very desirable margin of profit even at the start. The margin of additional profit or economic advantage obtainable by controlling the foregoing factors in the operation to the best practice attainable adds much to the competitive position of the manufacturer.

MANUAL METAL-ARC WELDING

Electrode Consumption

Distribution in Use of Electrodes.— The factors in Table 1 represent the

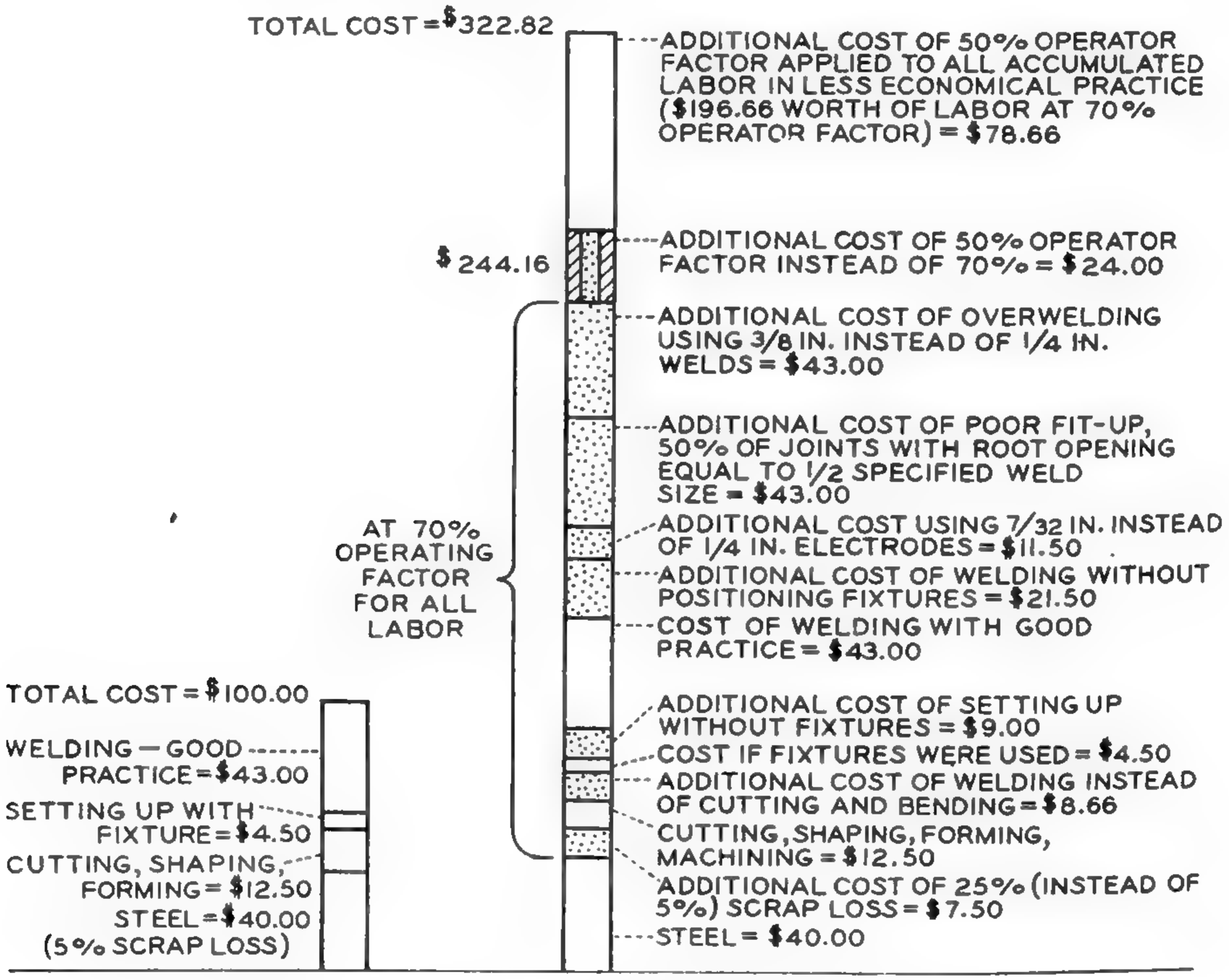


Fig. 8.—Cumulative Effect of Poor Practices on Total Cost

These differences when accumulated may look to be very large. In actual practice, careful study with a stop watch and other accurate measuring devices indicates that they are of such great importance that they represent the largest common margin for economic improvement in arc welding.

New applications of arc welding in manufacturing seldom begin at the highest degree of obtainable good practice, yet

average distribution in use for $^{3}/_{16}$-in. diam. E6010 electrodes used on medium size welds on an ordinary size job.

This flexible breakdown is adapted to any specific task of welding by filling in the best known quantities first, the least known last, and having the parts in each column add up to 100%. This process can be started any place in the table, but it is most expedient to start with the percent of coating for this is actually

a definite physical quantity which is a matter of knowledge, while all other factors are matters of practice.

To illustrate the use of Table 1 lay a piece of tracing paper over it and fill in the spaces in each column that apply to the case making each column total 100%. For example, if the total coating is 18% of the total weight of the electrode, put down 18 in line 5 column D, and 82 in 6D. If the electrode is 18 in. long and 16 in. are melted, put down 89 in 8C and 11 in 7C. The spatter loss depends on the position of welding and the current used. Coating is lost as spatter, but the coating already has been figured, so if the metal lost in spatter is 8% of the metal melted put down 8 in 9B, and 92 in 10B. If no chipping is done on this joint neglect lines 11 and 12. If none of the electrode is used for tacking, and the waste is negligible, put down zeros in 2E and 3E, and 100 in 4E. Upon completion of the table add all of the percentages in each column which represent a loss (coating 18%, stub ends 9%, spatter 6% = 33% total) and substract this sum from the total electrodes (100%). The difference (67%) represents the amount of metal deposited in the finished job. The amount of electrodes to be bought for a job can be determined from the relation

$$\frac{\text{Electrodes Purchased}}{\text{Metal Deposited}} = \frac{100}{67}$$

∴ for 100 lbs. deposited metal:

$$\text{Electrodes Purchased} = \frac{100}{67} \times 100 = 149 \text{ lb.}$$

Thus it is found that for every 100 lb. of metal deposited, 149 lb. of electrode must be bought.

Electrode Factors.—In Table 2 lines 1 and 2 show factors which are physical constants, but lines 3 to 28 show factors which are variable according to the manner in which the different electrodes are made and used. It should be recognized, therefore, that for each classification of electrode, lines 4 to 7 depend on the percent coating, lines 8 to 13 depend on the current and lines 14 to 21 depend on the position of welding and the type of joint. Proper allowances must be made for the factors for every combination of circumstances.

Converging Estimates.—Tables 1 and 2 do not necessarily give the answers directly, but they always show the method by which the answers can be found.

Table 1—Distribution of Electrode, % Weight

Line	Column →	A	B	C	D	E	F	G
1	Electrode bought	...	...	...	...	100	164	182
2	Used for other than welding, or wasted	...	...	...	.	3	5	5
3	Tacking, scaffold, jigs	...	...	...	...	7	11	13
4	Electrode used to weld seams	...	...	...	100	90	148	164
5	Coating	...	...	...	10	9	15	16
6	Metal used to weld seams	...	...	100	90	81	133	148
7	2-in. stubs of 14 in. electrodes	...	...	14	13	12	20	22
8	Metal melted	...	100	86	77	69	113	126
9	Spatter—metal only	...	12	10	9	8	13	15
10	Metal deposited	100	88	76	68	61	100	111
11	Metal chipped out	10	9	8	7	6	...	11
12	Metal in finished weld	90	79	68	61	55	...	100

NOTE: This table gives the average distribution of a 3/16 in. diam. E6010 electrode used on medium size welds on an ordinary size job. When making up this table for any specific task fill in the best known quantities first, the least known quantities last, and have the parts in each column add up to 100 %.

There can easily be a welding problem for which not a single one of the factors used in these tables is correct, and for which the values of the factors are unknown, but the tables will still be the nearest road to a theoretical solution of the problem. They also will bring into evidence the items which should be actually determined by tests beforehand, or checked on the job as soon as construction starts.

Every factor has natural limits and natural functions. For example, the percent of coating affects the quantity of electrode to buy but not the quantity deposited; the arc time in manual welding will never be 100%, and so on. The point is that even if the numerical value of a factor is unknown, the nature of the factor is known, and its importance will be apparent from its place in the

Table 2—Factors for E6010 Electrode—Flat Position

Line	Electrode, Diam., In. →			3/32	1/8	5/32	3/16	7/32	1/4	5/16	3/8
1	Lb. of metal in 12 in. of electrode			0.0235	0.0417	0.0652	0.0939	0.1278	0.1669	0.2608	0.3755
2	Ft. of electrode per lb. weld metal			42.50	23.97	15.34	10.65	7.825	5.992	3.834	2.663
3	Total length of electrode, in.			12	14	14	14	18	18	18	18
4	Total coating, % of total weight			15	12	10	8	10	10	12	14
5	Total metal, % of total weight			85	88	90	92	90	90	88	86
6	Weight of one complete electrode, lb.			0.0277	0.0552	0.0845	0.1190	0.2120	0.2780	0.4440	0.6550
7	Electrodes per lb. full length, coating incl.			36.10	18.08	11.83	8.403	4.717	3.597	2.252	1.526
8	Arc volts			24	25	26	28	30	31	32	33
9	Current, amp.			60	100	140	180	220	280	365	460
10	Arc seconds to melt 12 in. of electrode			60	60	65	70	75	80	90	100
11	Ft. of electrode melted per arc hr.			60	60	55.38	51.43	48	45	40	36
12	Lb. metal melted per arc hr.			1.41	2.50	3.61	4.83	6.13	7.51	10.4	13.5
13	Spatter/metal melted, %			12	14	16	18	20	22	24	25
14	Deposited metal/metal melted, %			88	86	84	82	80	78	76	75
15	Lb. metal deposited per arc hr.			1.24	2.17	3.04	3.95	4.92	5.85	7.90	10.2
16	Ft. electrode melted to deposit 1 lb. metal			48	28	18	13	10	7.7	5.0	3.5
17	Arc time, %			58	60	60	60	63	64	64	65
18	Arc min. per hr.			34.8	36	36	36	37.8	38.4	38.4	39
19	Lb. metal deposited per hr.			0.72	1.30	1.82	2.37	3.10	3.75	5.06	6.63
20	Hr. to deposit 1 lb. of metal			1.39	0.77	0.55	0.42	0.32	0.27	0.20	0.15
21	Ft. of electrode melted per hr.			34.8	36.0	33.2	30.8	30.2	28.8	25.6	23.4
22	Output at the arc, kwhr. per arc hr.			1.44	2.50	3.64	5.04	6.60	8.70	11.70	15.20
23	Kwhr. at the arc per lb. deposited			1.16	1.16	1.20	1.27	1.34	1.48	1.48	1.50
24	Heat input into joint Btu. per hr.			2860	5150	7450	10,300	14,200	19,000	25,600	34,000
25	Approximate lb. of metal deposited per hr.	Arc time as above	Flat	0.7	1.3	1.8	2.4	3.1	3.8	5.1	6.6
26		× 0.9	Horiz.	0.6	1.2	1.6	2.2	2.8	3.4	4.6	6.0
27		× 0.8	Vert.	0.5	1.1	1.4	1.9	2.5	3.0	...	...
28		× 0.6	O.H.	0.4	0.8	1.1	1.5	...	...	...	...

tables; therefore unknown factors can be given reasonable trial values and placed in Tables 1 and 2. When these are completely filled in, all the factors must work together to produce the final result. A check of the tables may result in some adjustments in the least known factors, and a subsequent check may result in further changes, and so on until all the knowledge and judgment of the estimator have been brought out and applied to carry the result closer and closer to the actual conditions.

Table 3—Pounds of Metal Melted per Arc Hr.

Line	Electrode Diam., In →		3/32	1/8	5/32	3/16	7/32	1/4	5/16	3/8
1	Lb. of metal per 12 in of electrode	→	0.0235	0.0417	0 0652	0.0939	0 1278	0.1669	0 2608	0 3755
2	Ft. of electrode per lb metal	→	42 50	23 97	15 34	10 65	7.825	5 992	3 834	2.663
	Melting Time, or Arc Sec. to Melt 12 In. of Electrode	Melting Rate, or Ft. of Electrode Melted per Arc Hr								
3	20	180	4 23	7.51	11 74	16 90	23 00	30.04	46.94	67.59
4	22	163 6	3 84	6 82	10 67	15 36	20 91	27.30	42.67	61.43
5	24	150	3 53	6 26	9 78	14 09	19 17	25 01	39.12	56.33
6	26	138 5	3 26	5 76	9 03	13 01	17.70	23 12	36.12	52.01
7	28	128 6	3 02	5 36	8.38	12 08	16.45	21 46	33.54	48.29
8	30	120	2 82	5 00	7.82	11 27	15 34	20 03	31 30	45 06
9	33	109 9	2 42	4 29	6.71	9 66	13 15	17.17	26.84	38 64
10	40	90	2 12	3 77	5 87	8 45	11 50	15 02	23.47	33.80
11	45	80	1 88	3 34	5 22	7 51	10 22	13 35	20 86	30 04
12	50	72	1 69	3 00	1 69	6 76	9 20	12 02	18.78	27.04
13	55	65 45	1 54	2 73	4 27	6 15	8 36	10 92	17.07	24.58
14	60	60	1 41	2 50	3 91	5 63	7.67	10 01	15.65	22.53
15	65	55 38	1 30	2 31	3 61	5 20	7 08	9 24	14.44	20.80
16	70	51 43	1 21	2 15	3 35	4 83	6 57	8.58	13 41	19.31
18	75	48	1 13	2 00	3 13	4 51	6 13	8 01	12.52	18 02
19	80	45	1 06	1 88	2 93	4 23	5.75	7.51	11.74	16.90
20	85	42 35	0 995	1 77	2 76	3 98	5 41	7 07	11.04	15.90
21	90	40	0 940	1 67	2 61	3 76	5 11	6 68	10.43	15.02
22	95	37 89	0 890	1 58	2.48	3 56	4 84	6 32	9 88	14.23
23	100	36	0 846	1 50	2.35	3 38	4 60	6 01	9 39	13.52
24	110	32.73	0 769	1 36	2 13	3.07	4 18	5.46	8.54	12.29
25	120	30	0 705	1.25	1 96	2 82	3.83	5 01	7.82	11.27
26	130	27 69	0 651	1 15	1 81	2 60	3 54	4 62	7.22	10 40
27	140	25 71	0 604	1 07	1 68	2 41	3 29	4 29	6.71	9 65
28	150	24	0 564	1 00	1 56	2 25	3 07	4 01	6 26	9 01

NOTE This table applies to all electrodes of the same specific gravity 7.85, the same as steel

Melting Time, Melting Rate and Quantity of Metal Melted.—The *melting time* is the number of seconds used to melt one foot of electrode. The *melting rate* is the feet of electrode melted per arc hour. The *quantity of metal melted* depends on the melting rate and the diameter of the electrode and on nothing else. Table 3 shows melting time, melting rate and quantity of metal melted per arc hour.

Quantity of Metal Deposited.—The metal melted is either deposited in the joint or lost as spatter. Generally, when the melting rate is increased the percent of spatter is also increased and the percent deposited is decreased. The percent spatter also varies with the diameter of electrode, the type of electrode, the position of welding and the type of joint used.

If the percent spatter were constant a greater melting rate would always give a greater quantity deposited, but as the melting rate increases there is, for some electrodes, a point beyond which the increase in spatter uses up more metal than is supplied by the increase in the quantity melted. This is the point of maximum deposition rate. The point of maximum deposition rate lies within the workable melting rate for some electrodes, but for others it is found at a greater current than is consistent with good practice in which case the maximum practical current controls the maximum deposition rate.

The two cases are illustrated in Fig. 9. An E6010 electrode is pictured as having the point of maximum deposition rate in the region of workable current and the deposition curve has a smooth crest. This means that a small variation in current will not materially affect the quantity of metal deposited in a certain time although the quantity of metal melted varies directly with the current. The deposition curve of the E6013 electrode is pictured as having no crest; the percent spatter does increase with the current and the melting rate but not fast enough to consume the additional metal melted. In this case the maximum workable amperage is the limit on the quantity of metal deposited per arc hour.

Arc Time

Arc time is the part of the welder's total work time in which the welding arc is in action. The arc time can never be 100% in manual welding, for a certain amount of time is required to change electrodes, etc.; but the arc time can be increased by organizing the working crew so that the welder is not delayed by miscellaneous tasks which can be performed by others.

Table 2 shows a 60% arc time for $^3/_{16}$-in. E6010 electrodes in the flat position. This figure is often attained welding straight runs but variations from 30 to 75% arc time are also common depending upon the type of structure, the position of welding, the makeup of the crew, and the experience of the welding operator. Table 2 shows other factors which influence the arc time: the rise from 60 to 63% is a result of changing from 14- to 18- in. electrodes and the rise from 63 to 65% is the result of increasing the melting time from 75 to 100 seconds. Both factors increase the length of arc time between interruptions and thereby the total arc time in a given period.

The quantity of welding produced in a day is directly proportional to the percent of arc time, other factors being constant.

Production Estimates

Any large footage of weld of a certain type, size, position, etc., should be given a special study, which can be guided by:

1. The ideal cross-section of the joint.
2. The quality of fit-up.
3. The actual cross-section of the finished weld.
4. The calculated pounds deposited per ft. of weld.
5. The assumed percent spatter.
6. The calculated amount of electrode melted per ft. of weld.
7. The assumed melting time.
8. The assumed percent arc time.

These factors juriciously applied will produce a converging estimate which probably will give the best possible theoretical solution. However, the estimator is in a far better position if he has production records or can arrange trial runs in the field or in the laboratory. Then he can forget about points 1 to 5 and deal with:

(*a*) Observed amount of electrode melted per ft. of joint.
(*b*) Observed melting time.
(*c*) Observed percent arc time.

For example:

(*a*) 3 electrodes melted per ft. of joint.
(*b*) 60 sec. melting time per ft. of electrode.
(*c*) 50% arc time and 3600 sec. per hr.

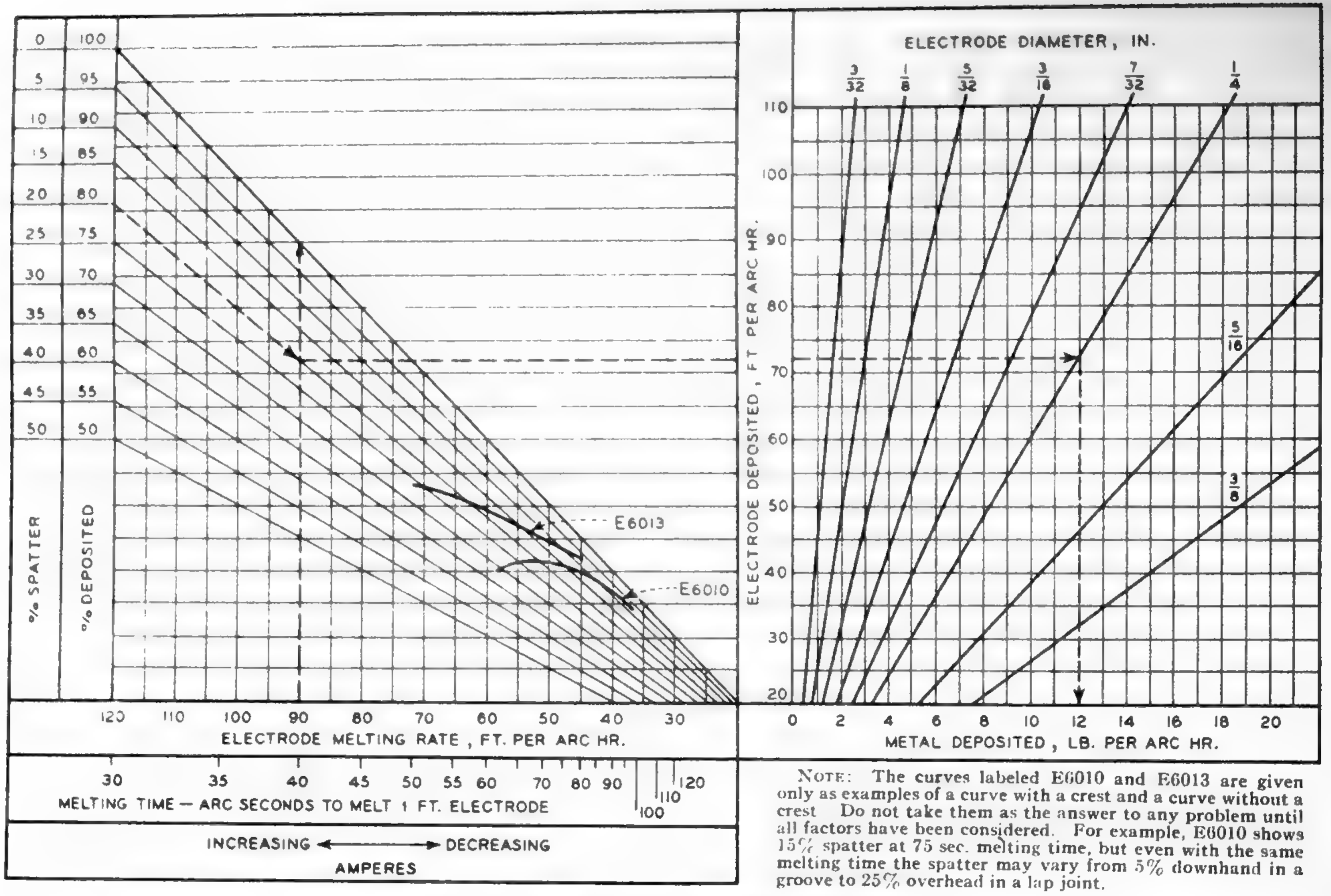
$$\frac{3600\times50}{3\times60\times100} = 10 \text{ ft. welded per hr.}$$

This is called the *three-factor method of estimating*.

The Three-Factor Estimate

It has been customary to estimate all types of welded joints in terms of the quantity of weld metal deposited per ft. of joint and such quantities have been determined at great effort by estimators and in laboratories. The 1942 edition of the AWS WELDING HANDBOOK, for example, gives long lists of values for different types of joints. The unfortunate aspect of this method is that there is usually no way of checking the results in the field, that is, it is usually not practical to weigh a structure before and after it is welded, and therefore a convincing proof of the accuracy of weight allowances is difficult to produce.

A three-factor estimate is, in the first place, no more or less accurate than a weight estimate when both are based on the same data and tests, but the three-factor estimate is open faced, its factors

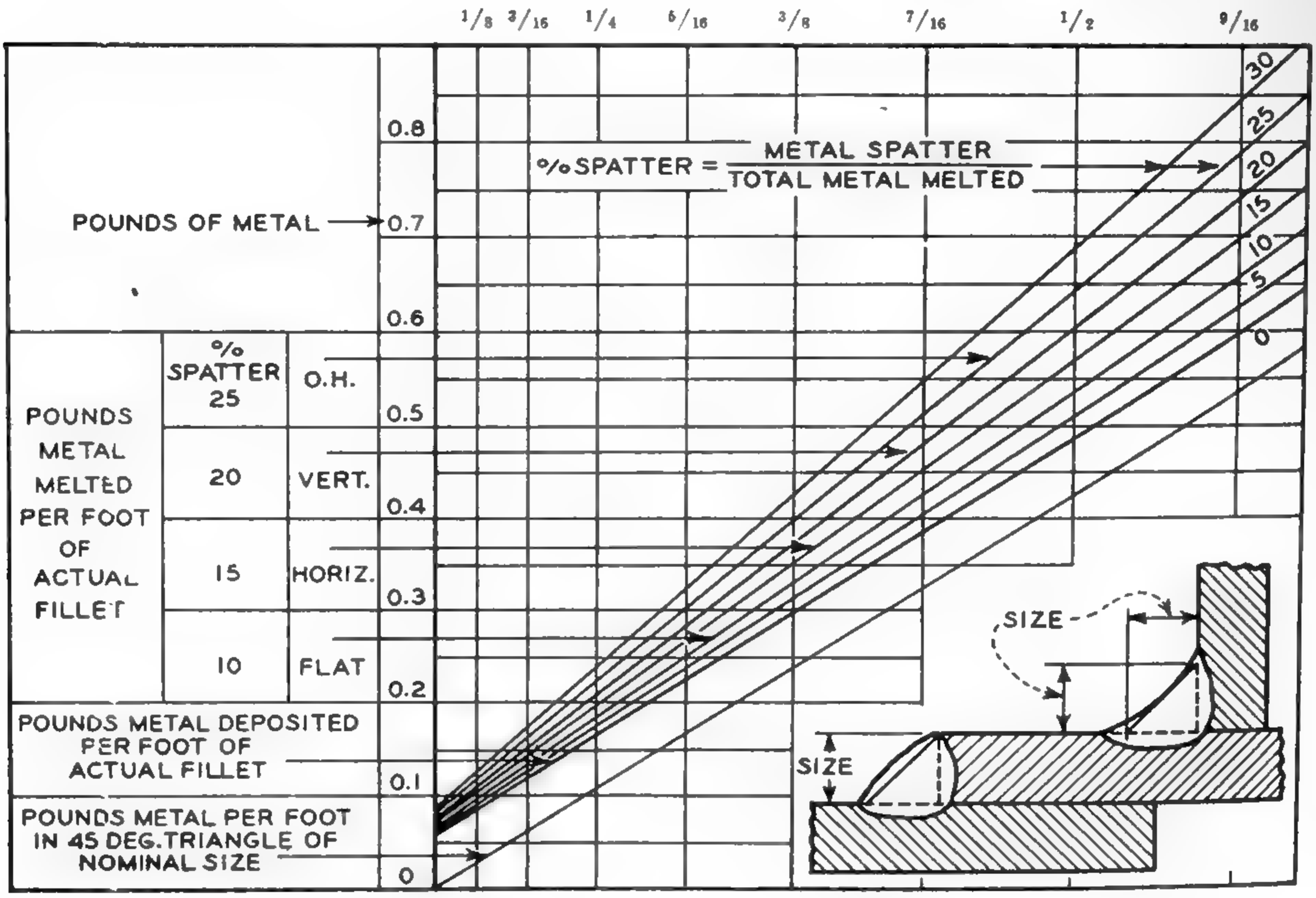


NOTE: The curves labeled E6010 and E6013 are given only as examples of a curve with a crest and a curve without a crest Do not take them as the answer to any problem until all factors have been considered. For example, E6010 shows 15% spatter at 75 sec. melting time, but even with the same melting time the spatter may vary from 5% downhand in a groove to 25% overhead in a lap joint.

Fig. 9.—Deposition Factors for Different Electrodes

are expressed in simple language which means the same to the Chief Engineer and the welder, to the seller and the buyer. This common ground of understanding is very important, but the greatest value of the three-factor method is that the actual value of each factor can be observed in practice. The feet of electrode melted per ft. of joint and the melting time can be checked by anyone with a rule and an ordinary watch, and instruments to determine the arc time are commonplace.

The three-factor estimate is equally applicable to all types and all units of welding, fillet welds or butt welds, individual joints or complete assemblies. This method can be used by itself or as a supplement to weight estimates or together with whatever data is on hand pertaining to each problem.



Nominal size of fillet, in.	1/8	3/16	1/4	5/16	3/8	7/16	1/2	9/16
Sq. in. of throat in 1 in. length of nominal-size weld	0.088	0.133	0.177	0.221	0.265	0.309	0.354	0.398
Lb. metal per ft. in 45 deg. triangle of nominal size	0.0265	0.0598	0.1061	0.1659	0.2390	0.3254	0.4250	0.5379
Lb. metal deposited per ft. of actual size	0.086	0.12	0.16	0.22	0.30	0.38	0.48	0.60
Comparative allowable strength of weld	2	3	4	5	6	7	8	9
Comparative quantity of metal in actual fillet per unit allowable strength	108	100	100	112	125	137	150	165

	Diameter, In.	Spatter, %								
Feet of electrode melted per foot of weld	5/32	25	O.H.	1.8	2.5	3.3	...	...	...	...	...
	3/16	20	Vert.	1.2	1.6	2.1	2.9	4.0	5.0	6.4	8.0
	7/32	15	Horiz.	...	1.1	1.5	2.0	2.8	3.5	4.4	5.5
	1/4	10	Down	...	...	1.1	1.5	2.0	2.5	3.2	4.0
	5/16	10	Down	...	...	...	1.0	1.3	1.6	2.0	2.6

Fig. 10.—Fillet Weld Data

Fillet Welds

Figure 10 gives data on fillet welds. The graph makes the same allowance for

lap joints and tee joints and it does not distinguish between different types of structures. The values given in the graph are adequate for small assemblies with simple welding and for larger assemblies with both lap and tee joints in several positions, because such assemblies will fall near the average anyway.

Groove Welds

The logical first observation to make of a groove weld is the cross-sectional area to be filled in with weld metal. It is true that this area, and thereby the quantity of weld metal deposited, is affected by the tolerance in preparing the plate edges, the actual spacing and alignment of the plates, the shrinkage which occurs during welding, and the final contour of the weld; but the first step toward an economical groove weld is to design a joint with as small a cross-sectional area to be filled as is practical.

Table 4—Estimate or Production Record

Col. 1	2	3	4	5	6	7	8	9	10
Pass No	Position of Welding	Electrode Diam., In.	Current, Amp	Sec to Melt 12-In. Electrode	Electrode Melted per Ft. of Joint, Ft	Metal Deposited per Ft. of Joint, Lb.	Arc Min. per Ft. of Joint	Arc Min. per Hr.	Ft. of Joint Welded per Hr.
1	Vert	5/32		60	1.8	0.10	1.8	..	..
Balance	Vert	5/16		80	8.8	0.70	11.7	..	..
Totals.					10.6	0.80	13.5	30	2.22

For best economy the largest diameter electrodes should be used, and the welding grooves should be wide enough to permit easy manipulation of the electrode. Closing the bottom of the groove—that is zero root opening—will mean a smaller open cross-section, but it may mean more feet of electrode melted to produce heat to fuse the parts. The design of the joint may also be controlled by the cost of edge preparation.

The form of Table 4 is useful both for making an estimate and for checking the factors in actual production. Let us suppose that no production records are available for the joint in question, and on the basis of the cross-sectional area it is decided that it is required to deposit 0.80 lb. of weld metal per ft. of joint, of which quantity 0.10 lb. will be deposited in the first pass with 5/32-in. diam. electrode, and the balance, or 0.70 lb. per ft., will be deposited with 5/16-in. diam. electrode. Fill in these quantities in Column 7. The spatter loss will probably be 15%. On that basis Table 5 gives the feet of electrode melted to deposit 1 lb. and this results in the figures of 1.8, 8.8 and 10.6 in column 6 of Table 4. Based on melting times of 60 and 80 sec. the arc min. per ft. are 1.8, 11.7 and 13.5 in Column 8. Finally, at 30 arc min. per hr. it is estimated that the production will be 2.22 ft. welded per hour.

To the same degree as the actual production misses the mark of 2.22 ft. per hr. some factor in columns 5, 6 or 9 is in error. If an error exists, it can be located with a rule and a watch and a few observations on the job. Such simple measurements can positively determine every figure in columns 5, 6 and 10, and these results will yield the true values for columns 8 and 9.

After the facts are recognized, the facts and figures can be brought to correspond, and in this manner, what started out as an estimate is turned into a production record. Such records make the logical foundation for other estimates, for each one is really a solved equation of the factors and data involved in estimating the cost of welding.

The Cost Estimate for Manual Arc Welding

A cost estimate based on the laws of economics often governs the selection of designs which in the first place are based on functional requirements and structural properties. All estimates are based on experience, and therefore the basis for cost estimates is cost records whether these be based on statistical or individual experience.

The following parts comprise a cost estimate:

1. Direct calculations based on known factors, extensive cost records,

contracts in existence, quotations on material, freight rates, power rates.

2. Projected calculations based on factors not entirely known, going beyond cost records, larger sizes, new shapes, new processes, contracts to be let.

3. Assumptions based on judgment and consideration of current trends, hazards, acts of man, acts of God.

Many of the values used are taken from the preceding charts and tables.

All costs given are fictitious and no amounts are stated, but the figures given for each item represent the percentage of total direct cost based on the total for the first design as 100.

Note that a change in one item changes the overall value, or the overall importance, of all items; but a change in one item does not affect the relation of a second item to a third item. For example, if the cost of railroad freight increases, welding will become a smaller percentage of the total cost, but this does not affect the relative cost of welding and painting.

In actual estimating there will be many advantages in showing dollar costs instead of percentages.

This sample estimate will illustrate both the outline and the procedure for estimating.

Table 5—Feet of Electrode Melted to Deposit 1 Lb. Metal

Line	Electrode Diam., In. →		3/32	1/8	5/32	3/16	7/32	1/4	5/16	3/8
1	Lb. of metal in 12 in. of electrode →		0.0235	0.0417	0.0652	0.0939	0.1278	0.1669	0.2608	0.3755
2	Ft. of electrode per lb. metal →		42.50	23.97	15.34	10.65	7.825	5.992	3.834	2.663
	% Spatter = Metal Spatter/ Total Metal Melted	% Deposited = Metal Deposited/ Total Metal Melted								
3	0	100	42.50	23.47	15.34	10.65	7.825	5.992	3.834	2.663
4	5	95	44.74	25.23	16.15	11.21	8.237	6.307	4.036	2.803
5	10	90	47.22	26.63	17.04	11.83	8.694	6.658	4.260	2.959
6	15	85	50.00	28.20	18.05	12.53	9.206	7.049	4.511	3.133
7	20	80	53.13	29.96	19.18	13.31	9.781	7.490	4.793	3.329
8	25	75	56.67	31.96	20.45	14.20	10.43	7.989	5.112	3.551
9	30	70	60.71	34.24	21.91	15.21	11.18	8.560	5.477	3.804
10	35	65	65.38	36.88	23.60	16.38	12.04	9.218	5.898	4.097
11	40	60	70.83	39.95	25.57	17.75	13.04	9.987	6.390	4.438

NOTE: This table applies to all electrodes with core metal of the specific gravity 7.85, the same as steel.

In weighing the cost of one design against the cost of an alternative design an estimate should deal with:

1. Constants or controlling factors, such as overall dimensions, time of completion, specifications.
2. Variables or controlled factors, such as dimensions of details, equipment and labor required for details, grade of material (which can alter allowable stresses and alter total weight).

Estimates which do not go beyond experience can be made with precision, but the introduction of every unsettled factor reduces the actual precision of the estimate, and in that case most figures beyond three significant places are mere window dressing.

Sample Estimate

A structure with very simple details is used in the following example (Charts 1 through 4 showing estimate No. 2203) which compares the merits and costs of several designs. Design in this sense includes the entire process of fabrication.

Outline of Steps Taken in Estimating

1. State the Problem (define the task and the time).
2. List the Constants (the final properties of the structure).
3. Pick a Working Unit (make the unit a quantity which the mind can comprehend, which could be used in reality, and which contains the recurring features of the structure).
4. Estimate the Constants (estimate all items which will be the same for all designs considered).

Chart 1

ESTIMATE NO.—2203 MADE—T.A. 2-8-48 APPR.—S.F. 2-8-48 PAGE 1 OF 3

UNIT—100 Ft. Pipe, 30 In. I.D., ½-In. Plates OPERATION—Planning

The Task: Fabricate a pipe line and deliver assembled in trench.
The Time: Install in trench progressively in 8 months.

Constants: Plate thickness ½ in.; I.D. = 30 in.; O.D. = 31 in.
Circumferential plate length = 96 in. = 8′0″.
Plates weigh 20.4 lb. per sq. ft.
Plain pipe weighs 163.2 lb. per ft., 861,696 lb. per mile.
Total weight = 17,233,920 lb. = 8,617 tons.
Total length = 105,600 ft. = 20 miles.

Time: 8 months (×52/12) = 34.7 weeks, (×5) = 173 work days
105,600/173 = 610 ft. installed per work day = 99,500 lb.

Design A—Shop Assembly	6 Lengths @ 8 ft. = 48 ft.	=	7,840 lb.
Assemble alongside trench	7 Lengths @ 48 ft. = 336 ft.	=	54,880 lb.
Assemble over trench	2 Lengths @ 336 ft. = 672 ft.	=	109,760 lb.
Design B—Shop Assembly	5 Lengths @ 9 ft. = 45 ft.	=	7,350 lb.
Assemble alongside trench	8 Lengths @ 45 ft. = 360 ft.	=	58,800 lb.
Assemble over trench	2 Lengths @ 360 ft. = 720 ft.	=	117,600 lb.
Design C—Shop Assembly	1 Length @ 30 ft. = 30 ft.	=	4,900 lb
Assemble alongside trench	12 Lengths @ 30 ft. = 360 ft	=	58,800 lb
Assemble over trench	2 Lengths @ 360 ft. = 720 ft.	=	117,600 lb

5. Estimate the Variables (take each design separately and estimate the remaining items it contains).

6. Compute the Final Estimate (the total estimate will be the constants plus the variables).

In the comparison of designs A, B, and C (Charts 1 through 4), it is noteworthy that savings are accomplished by eliminating welding. Design C has reduced the footage of welding by one-third; this reduces the welding cost by 6% of the overall and it also reduces the cost of fabrication by 6% of the overall cost even though the cost of forming a plate is three times as much in Design C as in Design A.

Chart 2

ESTIMATE NO.—2203 MADE—T.A 2-8-48 APPR.—S F. 2-8-48 PAGE 2 OF 3

UNIT—100 Ft. Pipe, 30 In. I.D., ½ In Plates OPERATION—Summary

Line	Item	Material	Equip	Labor	Cost of Item	No. in Unit	Totals per Unit
1	16,320 lb. plates	38	..		38	1	38
2	Fabrication and handling					...	..
3	Unloading, handling, loading	..	1	2	3	...	...
4	Unloading, hauling and placing in trench	.	4	6	10	...	...
5	Sandblasting		1	1	2	...	..
6	Painting	1	..	1	2	...	...
7	Welding one long seam using sheared plate edges	1	1	6	8	...	...
8	Subtotal	2	7	16	25	1	25
9	Railroad freight	..	..	..	16	1	16
10	Items common to all designs—constants	40	7	16	16	...	79
11							
12	Design A: 6 @ 8 ft. = 48 ft.	7 @ 48 ft. = 336 ft.			2 @ 336 ft. = 672 ft.		
13	Shearing one plate on four sides	.	0.06	0.07	0.13	...	...
14	Planing two edges for circumferential seam	.	0.21	0 26	0.47	...	...
15	Rolling one plate and tacking long. seam	..	0.06	0.14	0.20	...	...
16	Subtotal	..	0.33	0.47	0.80	100/8	10
17	Fitting and welding splice in shop	0.10	0.17	0.40	0.67	$5 \times \frac{100}{48}$	7
18	Fitting and welding splice alongside trench	0.10	0.10	0.90	1.10	$6 \times \frac{100}{336}$	2
19	Fitting and welding splice over trench	0.10	1.00	2.30	3.40	100/336	1
20	Painting field splices	0.20	..	0 26	0.46	100/48	1
21	Details of Design A, Variables	..	..	..	..	...	21
22	Design A, Constants	..	..	..	..	...	79
23	Design A, Total	..	..	.	..	...	100

Manual Arc Welding Stainless Steel

In welding stainless steel, the general factors influencing welding cost as outlined above bear at least the same relative importance as with other ferrous materials, and probably even more, due to the fact that both the materials and electrodes for stainless steel welding usually are more expensive than for most other ferrous materials.

For purposes of cost estimation, Fig. 10 given in the previous section may be used to estimate the amount of weld metal required for various sizes and types of joints. Figure 11 shows in graphic form the approximate deposition rates for commercial stainless electrodes having lime type coatings. Titania type coatings usually show rates slightly below the shaded area in Fig. 11.

The quantity of electrode required for a given joint may be estimated from the following formula:

$$W = \frac{28V}{E(100-S)}$$

where

W = Lb. of electrodes required
V = Volume of filler metal in cubic inches
E = Deposition efficiency (ratio of weight of weld metal to weight of consumed electrode), %
S = Stub loss, %

Chart 3

ESTIMATE NO.—2203 MADE—T.A. 2–8–48 APPR.—S.F. 2–8–48 PAGE 3 OF 3

UNIT—100 Ft. Pipe, 30 In. I.D., ½-In. Plates OPERATION—Summary

Line	Item	Material	Equip.	Labor	Cost of Item	No. in Unit	Totals per Unit
1	Design B: 5 @ 9 ft. = 45 ft.	8 @ 45 ft. = 360 ft.		2 @ 360 ft. = 720 ft.			
2	Shearing plate on four sides	..	0.05	0.06	0.11	...	..
3	Planing two edges for circumferential seam	..	0.21	0.24	0.45	...	..
4	Rolling plate and tacking longitudinal seam	..	0.06	0.10	0.16	...	..
5	Subtotal	..	0.32	0.40	0.72	100/9	8
6	Extra charge for extra-wide plates	2	..	..	..	...	2
7	Subtotal	..	..	..	..	...	10
8	Fitting and welding splice in shop	0.10	0.10	0.34	0.54	$4 \times \frac{100}{45}$	6
9	Fitting and welding splice alongside trench	0.10	0.10	0.80	1.00	$7 \times \frac{100}{360}$	2
10	Fitting and welding splice over trench	0.10	1.00	2.45	3.55	100/360	1
11	Painting field splices	0.20	..	0.26	0.46	100/45	1
12	Details of Design B, Variables	..	..	..	..	...	20
13	Design B, Constants	..	..	..	..	...	79
14	Design B, Total	..	..	..	..	...	99
15							
16	Design C: 1 @ 30 ft. = 30 ft.	12 @ 30 ft. = 360 ft.		2 @ 360 ft. = 720 ft.			
17	Shearing plate on four sides	..	0.08	0.10	0.18	...	..
18	Planing two edges for circumferential seam	..	0.24	0.18	0.42	...	..
19	Rolling plate lengthwise tacking longitudinal seam		0.33	0.27	0.60	...	..
20	Subtotal	..	0.65	0.55	1.20	100/30	4
21	Fitting and welding splice alongside trench	0.10	0.10	0.80	1.00	$11 \times \frac{100}{360}$	3
22	Fitting and welding splice over trench	0.10	1.00	2.45	3.55	100/360	1
23	Painting field splices	0.20	..	0.18	0.38	100/30	1
24	Details of Design C, Variables	..	..	..	..	...	9
25	Design C, Constants	..	..	..	..	...	79
26	Design C, Total	..	..	..	..	...	88
27							

Estimates of costs for manual arc welding of stainless steel may be built upon the plan described above for other manual arc welding estimates by listing the constant factors and estimating the varying factors as previously described.

Manual Metal-Arc Welding of Aluminum

The general factors discussed in the beginning of this chapter apply to estimating costs for manual metal-arc welding of aluminum as they do to welding other materials. The welding of aluminum is discussed in detail in Chapter 32.

In addition to the general factors previously discussed, estimates for manual welded aluminum fabrications should include special attention to two additional factors.

Preparing the parts for aluminum structures usually requires a machine cutting operation which, from a cost-estimating standpoint, is little different from the cutting and preparing of other metals, but which for shape cutting may be more expensive than oxygen cutting of ferrous materials.

A second factor which should be analyzed is the cost of cleaning welds after deposition. In some cases the cleaning process requires a chemical treatment, the labor, materials and equipment for which may involve a larger proportion of the overall cost of producing the structure than is commonly the case for welded ferrous structures.

Chart 4

Design	A	B	C
Constants	79	79	79
Variables	21	20	9
% of total cost	100	99	88
Longitudinal welds	8	8	8
Circumferential welds	10	9	4
All welds—% of total cost	18	17	12
Ft. of welding per 100 ft. of pipe:			
Longitudinal seams	100	100	100
Circumferential seams	100	89	27
Total ft. of welding	200	189	127
Ft. of welding, %	100	95	64

Cost estimates may be made for manual metal-arc welding of aluminum following the general plan of those previously given for manual metal-arc welding with ferrous materials, the electrode's deposition rates and other data being given in Chapter 32.

ATOMIC HYDROGEN ARC WELDING

Estimating costs for atomic hydrogen arc welding, either manual or mechanical, follows the general plan of estimating previously described. A description of the atomic hydrogen welding process is given in Chapter 11.

Data for computing atomic hydrogen welding costs in the following tables and paragraphs are based upon arc time only.

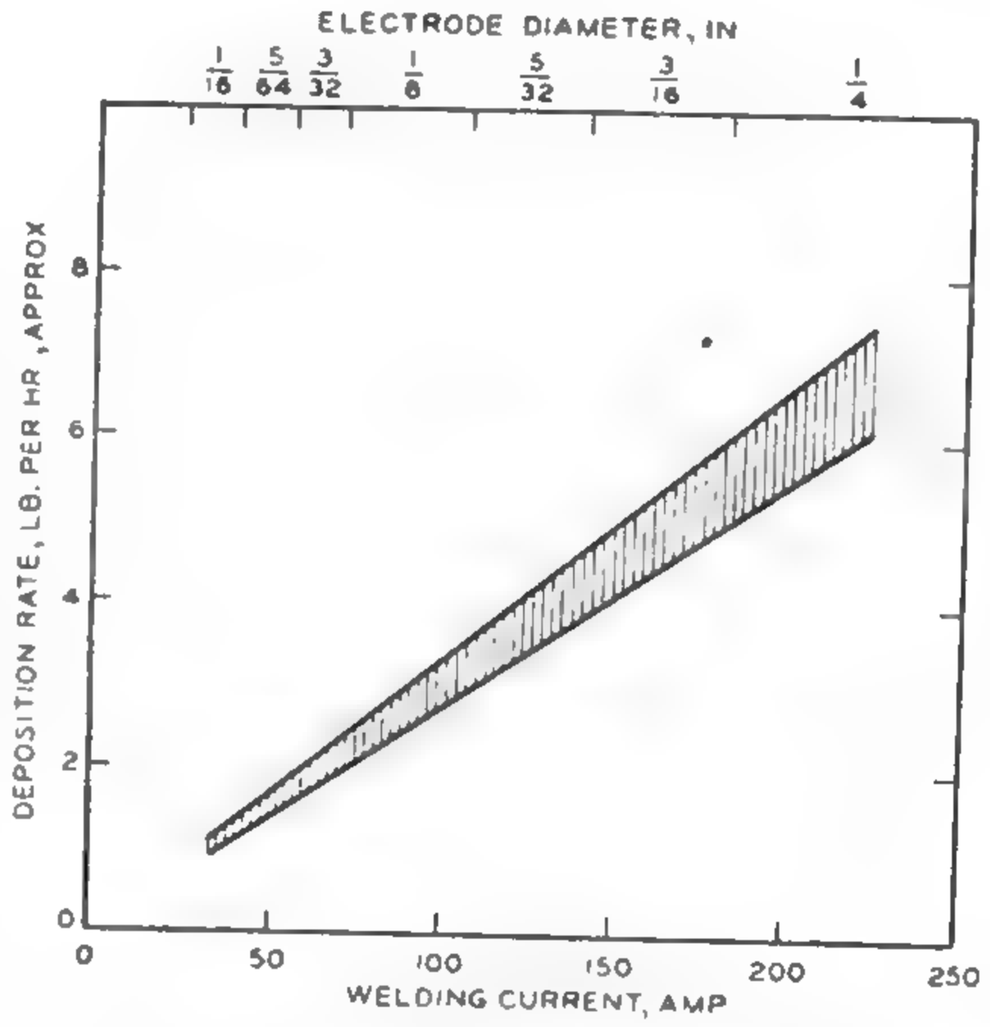


Fig. 11.—Deposition Rates for Stainless Steel Electrodes with Lime-Type Coverings

In making estimates for either manual or automatic atomic hydrogen welding costs, the list of factors shown in Table 1 must be expanded to include such elements as hydrogen consumed and tungsten electrode consumed, with such elements as electrode coating eliminated.

The general plan for estimating costs follows that for manual metal-arc welding previously outlined.

The data for manual welding are given in Tables 6 and 7. In using these data for computing welding time, the length of the seam should be increased to compensate for the time required to start and finish the weld and for intermediate pauses. A fairly accurate value is 1 in. plus an additional inch for each 2 ft. of length.

For automatic or machine welding, data are available for butt joints only, as other joint types are seldom used. Material having a thickness in excess of 3/16-in. is seldom welded by machine welding. When it is, a proper backing must be used or some equally effective method provided to avoid spill-through. For very thin material, magnetic sta-

Table 6—Manual Atomic Hydrogen Data for Various Thicknesses and Types of Joint

Lap Joint		Butt Joint		Corner Joint		Edge Joint			
Thick., In.	Speed, In./Min.	Thick., In.	Speed, In./Min.	Thick., In.	Speed, In./Min.	Thick., In.	Speed, In./Min.	Current, Amp.	Power, Kwhr.
1/32	Difficult	1/32	8–9	1/32	11–12	...	...	15–20	1.1
1/16	8–9	...	...	...	...	1/32	11–13	20–25	1.4
3/32	7.5–8.5	1/16	9–12	1/16	13–14	...	...	25–30	1.8
1/8	7–8	3/32	8–10	3/32	10–11	1/16	12–13	30–35	2.2
3/16	3.5–4.5	1/8	7–10	1/8	9.5–10	3/32	10–12	35–40	2.6
		3/16	3–3.5	...	...	1/8	9–10	40–45	3.0
1/4	2.5–3.5	...	...	3/16	4–5	...	...	45–50	3.5
		1/4	2.5–3	...	...	3/16	5.5–6	50–55	3.9
3/8	2–2.5	3/8	1–1.5	1/4	3–3.5	...	...	55–60	4.4
		...	...	3/8	2–3	1/4	4–4.5	60–65	4.9
		...	...	...	...	3/8	2.5–3.5	60–65	4.9
1/2	1.5–2	1/2	0.75–1	1/2	1.5–2	1/2	2–2.5	70–75	6.0
1/2	2–2.5	...	...	...	...	...	...	75–90	7.1
		1/2	1–1.5	1/2	1.75–2.5	1/2	2.5–3	90–100	8.5
	6–8[a]	...	6–8	...	6–8	...	6–8	100–120	10.1
1/2	7–9[a]	1/2	7–9	1/2	7–9	1/2	7–9	120–140	12.5
Up	8–10[a]	Up	8–10	Up	8–10	Up	8–10	150	15

[a] These speeds are expressed in cu. in. of filler rod deposited per hr.

bilization of position of the arc is necessary. For computing welding time, the data from Table 8 should be used. It should be noted that a much higher duty factor than for manual welding is usually obtained, and that no addition for the start and finish of the weld is necessary.

CARBON-ARC WELDING

In making cost estimates for either manual or automatic carbon-arc welding, the general factors influencing welding costs as outlined in the first section of this chapter exert their influence. The estimating plan as outlined for manual metal-arc welding shown in Table 1, with the deletion of electrode coating losses and the addition of flux costs, is also applicable to carbon-arc welding.

Automatic (Machine) Carbon-Arc Welding

Data covering automatic carbon-arc welding are given in Chapter 9. From these data, estimates of costs of making welds automatically with the shielded carbon arc can be made. The items and use of information are listed below. The cost values shown are not necessarily representative of any real values and it is assumed that appropriate values will be substituted in actual estimates.

Labor.—The price of labor for welding operators varies considerably due to local conditions, etc. For simplicity only, the figure used is $1.50 per hour.

Power.—Volts and amperes are given so that the amount of power is known. The efficiency of machines for carbon-arc voltage requirements can be taken as an average of 60%. Power cost is assumed as $0.02 per kilowatt-hour.

Electrodes.—The life of a 13½-in. or 19½-in. carbon electrode will vary from about ¾ to 3 hr. depending upon various conditions. For a basis of estimating costs the carbon consumption will be figured at $0.10 per hr., since carbon cost per ft. of welding is negligible.

Paste Type Flux.—Cost per lb. is as-

Table 7—Consumption Rates for Tungsten Electrode and Hydrogen

0.040 Elect.		0.062 Elect.		0.093 Elect.		0.125 Elect.		0.187 Elect.	
Tungs., In./Min.	Hyd., Cu. Ft./ Hr.	Tungs., In./Min.	Hyd., Cu. Ft./ Hr.	Tungs., In./Min.	Hyd., Cu. Ft./ Hr.	Tungs., In./Min.	Hyd., Cu. Ft./ Hr.	Tungs., In./Min.	Hyd., Cu. Ft./ Hr.
0.73	30	0.55	40	0.66	45	0.44	55	1.31	90
1.14	30	0.86	40	0.75	45	0.52	55	1.57	90
..	..	1.30	40	0.94	45	0.61	55	1.94	90
..	..	1.85	40	1.16	45	0.71	55	2.75	90
..	..	2.51	40	1.42	45	0.82	55	3.90	90
..	..	..	..	1.72	45	0.94	55	..	..
..	..	..	..	2.04	..	1.07	55	..	..
..	..	..	..	..	..	1.07	55	..	..
..	..	..	..	..	..	1.38	55	..	..

sumed as $0.35 and 1 lb. will cover an average of 300 ft. of seam.

Fibrous Flux.—Cost per lb. is assumed as $0.30 and there are 60 ft. in a pound. Assuming the flux feed is 8 in. per min., the average cost is $0.20 per hour.

Powder Flux.—Cost per lb. is assumed as $0.15 and it is consumed at the rate of 8 to 20 lb. per hour. Based on the heaviest to the lightest thicknesses given (where powder is used), the amount will vary in proportion to the speed of travel for a general-cost figure.

Filler Metal.—Cost per lb. is assumed as $0.075. Three different sizes are used. The ft. per lb. consumed are as follows:

$^{3}/_{32}$-in. diam.—43.5 ft./lb.
$^{1}/_{8}$-in. diam.—24.0 ft./lb.
$^{5}/_{32}$-in. diam.—15.4 ft./lb.

Price may vary according to quantity. Actual measurements of consumption of each item may be taken for a particular application.

The application of the carbon arc to the welding of aluminum is discussed in chapters 9 and 32 and the data there listed provide information upon which cost estimates may be made.

SUBMERGED ARC WELDING

The process of submerged arc welding is described in Chapter 13. For cost-estimating purposes the general factors described in the first section of this chapter are very important and all apply.

The control of the fit-up of the members of the joints is probably more important economically for this type of welding than for any other. The process as described in Chapter 13 stresses the importance of either very closely fitting joints or the use of a backing which will retain the fluid weld metal during deposition until it has fused the joint and solidified. Because of the great fluidity of the metal at the time of deposition, the metal may escape if the joints do not fit tightly, requiring expensive patching.

To produce high quality weld metal the joint must be clean. For best results, submerged arc welding like other processes, requires that all moisture, oil, mill scale, rust or other foreign materials be removed before welding.

The unusually high currents that are used provide a substantial economy of added weld metal and of labor costs. The high current fuses from 1 to $1^{1}/_{2}$ or even 2 times as much base material as the metal added. Similarly the high currents proportionately increase the rate of metal deposition and give higher welding speeds and lower labor costs. As an example $^{1}/_{4}$-in. diam. welding rod may be deposited at a rate of about 40 to 45 lb.

Table 8—Data for Machine Atomic Hydrogen Welding

Thickness, In.	Welding Current, Amp	Arc Voltage	Welding Speed, In./Min	Consumption Rates—Power, Kw	Hydrogen, Cu. Ft./Hr.	Tungsten, In./Hr.
0.015	35	50	140	3.2	60	1.2 } $^{1}/_{16}$ diam.
0.025	45	55	80	2.9	80	2.2 }
0.035	50	60	65	3.5	90	0.8 }
0.050	60	64	50	4.5	100	1.3 } $^{3}/_{32}$ diam.
0.065	68	65	37	5.2	110	2.2 }
0.078	75	65	30	5.6	120	3.0 }
0.094	83	68	22	6.5	120	1.5 }
0.109	87	68	18	7.0	120	1.8 }
0.125	95	70	16	7.6	120	2.0 } $^{1}/_{8}$ diam.
0.141	100	70	14	8.1	120	1.2 }
$^{9}/_{64}$	105	72	12	8.6	120	1.5 }
$^{5}/_{32}$	110	72	10	9.2	120	1.7 } $^{5}/_{16}$ diam.
$^{1}/_{4}$	120	75	7	10.2	120	1.8 }
$^{5}/_{16}$	130	75	5	11.0	120	1.9 }

The simplest way to figure direct costs is on an hourly basis and then allow for whatever efficiency factor for the particular application the shop uses. This may vary from 50 to 80%.

Example.—Edge joint in 12-gage sheet with no filler metal added.

Metal Thickness, Ga.	Arc Volts	Arc Amp.	Carbon Size, In.	Type of Flux	Welding Speed, Ft./Hr.
12	25	275	$^{5}/_{16}$	Paste	170

Direct cost—hourly basis:

Labor at $1.50 per hr. $1.50
Power at $0.02 per kwhr. $\frac{275 \times 25 \times 0.60}{1000 \times 0.60}$ 0.23
Carbon electrode at $0.10 per hr. 0.10
Flux—Paste at $0.35 lb. $\frac{1}{2} \times 0.35$ 0.17
Total cost $2.00
Cost per ft., 2.005/170. . . . . 0.0118

NOTE: The above method of figuring costs is based on actual arc time and does not take into consideration idle time or overhead

per arc hr. and with rods up to 5/8-in. diam. the deposit rate may reach 80 to 100 lb. per arc hour.

To obtain the true labor charge it is necessary to establish for any new job estimate the actual time that metal is being deposited during the full working period. This operating factor may vary from 15% for custom work to nearly 100% for continuous work and must be determined by experienced judgment or by actual trial.

Because the submerged arc process is usually mechanized and the metal must be deposited in joints which are either positioned for flat position welding, or occasionally for welding small joints in the horizontal-fillet position, some special tooling and mechanical positioning fixtures are necessary. Because of the cost of necessary fixtures, the welding head, current control and flux control mechanisms, the capital investment, compared to the labor costs, is greater than for the manual metal-arc processes. Therefore, for cost-estimating purposes, the factor of overhead charged against arc time or labor should be examined and possibly increased over that used for manual metal-arc welding, to represent accurately the capital investment of the submerged arc welding process equipment.

Since the filler metal and the granular flux are not combined, each must be controlled separately and calculated separately in the cost estimates. The control of the flux is especially important due to its granular nature and the possibility of its being lost or unused in the process.

In making a cost estimate, it should be kept in mind that there is no stub or spatter loss of the rod to be accounted for and that there is practically 100% deposit of all rod melted. The power requirement is about 1.5 kwhr. per lb. of metal deposited by alternating current and about 2.5 kwhr. per lb. by direct current. If a gasoline-driven engine is used for d.c. generation then a fair figure to use is about 1½ pt. of gasoline for each pound of metal deposited.

The amount of granulated welding composition that is used per lb. of weld metal applied is theoretically about one pound. However, depending upon the efficiency of the recovery methods in use the requirements may increase to 1.4 lb. and where little care is exercised it may amount to 2.5 pounds.

Table 9—Cost Data for Manual Oxy-Acetylene Welding

Thickness of Steel In.	Thickness of Steel Ga.	Joint Preparation (Spacing Zero)	Diam. of Rod, In.	Tip Size, Use Tip Consuming This Volume of Acetylene per Hr.	Material Requirements: Oxygen, Cu. Ft. Per Hr.	Material Requirements: Oxygen, Cu. Ft. Per Linear Ft. Welded	Material Requirements: Acetylene, Cu. Ft. Per Hr.	Material Requirements: Acetylene, Cu. Ft. Per Linear Ft. Welded	Rod, Lb. Per Hr.	Rod, Lb. Per Ft.	Speeds: In. per Min.	Speeds: Ft. per Hr.
1/4	28	Square groove	...	0.2– 0.7	0.7	0.03	0 7	0.03	.....	...	5.2–6.0	26 0–30.0
1/32	22	Square groove	...	0.6– 1.6	1.0	0.05– 0.04	1 0	0.05– 0.04	.....	...	4.4–5.0	22 0 25.0
1/16	16	Square groove	1/16	1.0– 3.2	2.4	0.13– 0.11	2 3	0.13– 0.11	0.23–0.27	0.013	3.6–4.2	18.0–21.0
3/32	13	Square groove	3/32	2.0– 7.0	5.1	0.36– 0.30	4 9	0 36– 0.29	0.42–0.51	0.030	2.8–3.4	14.0–17.0
1/8	11	Square groove	1/8	3.0– 12 0	8.8	0.80– 0.68	8 5	0 77– 0.65	0.58–0.69	0.053	2.2–2.6	11 0–13.0
3/16	7	90° Single Vee	3/16	6 0– 22.0	17.7	2.36– 2.08	17.0	2 27– 2.00	1.13–1.28	0.150	1.5–1.7	7.5– 8.5
1/4	3	90° Single Vee	3/16	10.0– 35.0	27.0	4.50– 3.86	26 0	4.33– 3.72	1.59–1.86	0.265	1.2–1.4	6.0– 7.0
5/16	0	90° Single Vee	1/4	25 0– 40.0	33.0	7.40– 6.05	32 0	7.11– 5 82	1.87–2.28	0.414	0.9–1.1	4.5– 5.5
3/8	3/0	90° Single Vee	1/4	30 0– 50 0	45.7	11.42– 9.13	44.0	11.0 – 8.80	2.39–2.98	0.597	0.8–1.0	4.0– 5.0
1/2	7/0	60° Single Vee	1/4	35 0– 65 0	58.2	11.65– 9 70	56 0	11 2 – 9.33	2.90–3.48	0.637	1.0–1.2	5.0– 6.0
5/8	...	60° Single Vee	5/16	45 0– 85.0	73 8	21 10–16 42	71.0	20 30–15 79	3.06–3.92	0.872	0.7–0 9	3.5– 4.5
3/4	...	60° Single Vee	5/16	60 0–105 0	91.5	36 60–26 16	88 0	35 20–25.17	3.27–4.57	1.307	0.5–0.7	2.5– 3.5

Chapter 13 presents the welding conditions for various joint designs including the weld metal requirements for each foot of weld. With the speed of welding and the metal requirements known, an accurate cost can be developed. In the following sample calculation the data are taken from Table 8, Chapter 13, for a single-pass weld in 1-in. plate:

Assume:

(*a*) 1 lb. of metal added per ft.
(*b*) Speed of welding—11 in. per. min.
(*c*) A.C. power—1½ kwhr. per lb. at $0.02 per kwhr.
(*d*) Operating factor—50%.

Cost per Foot:

(Based on a total price of $0.22 for welding rod and welding composition per lb. of metal added)

1. 1 lb. of weld metal per ft. = $0.22
2. Power per ft. (0.02 × 1.5) = 0.03
3. Labor per ft., at $1.50 per hr. (0.5 operating factor)

$$\frac{\$1.50 \times 12}{11 \times 60 \times 0.5} = 0.05$$

Total cost per ft. = $0.30

MANUAL OXY-ACETYLENE WELDING COSTS

The quality and quantity of welding produced by manual oxy-acetylene welding is dependent upon the skill and experience of the welder, a fact common to all hand operations. The work of the novice is slow and of doubtful quality. With increased practice and experience his skill is improved. If a welder works solely on one product he will ultimately develop a high degree of skill which, when compared with other operations by less skilled men, will indicate production speeds of very high order. Therefore, in publishing data for cost estimating it becomes necessary to establish average conditions with the full realization that considerable variations will be encountered under actual working conditions.

The data given in Table 9 represent values obtainable by average welders employing single flame tips. The governing conditions are set forth in the table. Actual job conditions have been assumed for this tabulation, hence allowance has been made for lost time, etc. It must be realized that the multitude of variables influencing manual oxy-acetylene welding renders it impossible to set definite values on the speed of welding and consequently on the amounts of oxygen, acetylene and welding rod consumed. Therefore, ranges are indicated for these factors. Obviously the slower speeds will be obtained with the less experienced welders and involve higher gas consumption while the higher speeds apply to the opposite condition. The only definite values provided are for pounds of rod deposited per ft. of weld, which figures are reasonably constant. The data on welding rod consumption assume weld reinforcements equivalent to about 25% of base metal thickness.

To avoid proprietary references, tip sizes have been expressed in terms of acetylene flow per hour. The governing factor in oxy-acetylene welding is the cubic feet of acetylene required to deposit 1 lb. of weld metal, hence this is the logical method for establishing proper tip sizes for given thicknesses. Data on acetylene flows for each tip size are generally available from equipment manufacturers.

BIBLIOGRAPHY

1. *Arc Welding in Design, Manufacture and Construction,* The James F. Lincoln Arc Welding Foundation, 1939.
2. *Studies in Arc Welding, Design, Manufacture and Construction,* The James F. Lincoln Arc Welding Foundation, 1943.
3. *Arc Welding Engineering and Production Control,* W. J. Brooking, McGraw-Hill Book Co., 1944.
4. *Procedure Handbook of Arc Welding Design and Practice,* The Lincoln Electric Co., Eighth Edition, 1945.
5. *Arc Welding Engineering Problems and Engineers,* W. J. Brooking, The Welding Journal, September 1945.
6. *Economics of Arc Welding,* W. J. Brooking, The Welding Journal, November 1945.
7. *Resistance Welding Manual,* Resistance Welder Manufacturers Assn., Revised Edition, 1946.

CHAPTER 42

INSPECTION OF WELDING*

INTRODUCTION

THIS CHAPTER sets forth some basic concepts regarding the qualification and duties of welding inspectors and describes the various inspection methods and test procedures used.

The information on inspectors is applicable to all types of inspectors whether employed by the manufacturer whose product is being inspected, by the purchaser of the product or whether employed by a regulatory body and not directly responsible to either the manufacturer or purchaser.

With regard to the inspection methods, it should be noted that all of them are not equally applicable to every type of fabrication. Which test procedures to use must be determined in each case according to code or specification requirements or on the basis of the severity of service conditions to which the completed product will be subjected.

REQUIREMENTS FOR A WELDING INSPECTOR

Essential Requirements

An inspector functions as the judicial representative of an organization which may be either the manufacturer, the purchaser or a government agency. It is his responsibility to see that the product he inspects is of sound quality. His decisions are governed by some form of written requirements which he has not drawn up, but which he must be able to interpret, both as to limitations and intent. Although he must strive for highest quality he must not unnecessarily retard prompt completion and delivery.

All of the following items are essential requirements that necessitate careful and thorough study and application. They must not be treated lightly if the inspector wishes to do a conscientious job.

Physical Condition.—An inspector's agility must be sufficient to permit him to fulfill his duties. Good inspection requires examination before, during and after fabrication, and this often entails climbing around large fixtures and assemblies. Inspection conditions are often difficult, as positioning of the work is primarily for the welder's convenience.

Vision.—Good vision is vitally necessary to a welding inspector to permit close visual inspection of welds, radiographs and magnetic powder indications. Nearly all welding inspection requires good eyesight for discerning small details.

Attitude.—The importance of an inspector's attitude cannot be over-emphasized. He is very much dependent on cooperation of his associates in all departments, and he must command their respect in order to obtain it. Since many of his decisions are made on marginal material, his judgment must be careful, impartial and consistent. A definite policy of inspection procedure and standards should be adopted and adhered to faithfully. An inspector should not be stubborn, nor yet easily swayed by persuasive arguments. Under no circumstances should he seek favor or incur obligation through his decisions. The most difficult period for an inspector is his first few weeks on any new location, since those with whom he deals will be testing him for weakness in policy. If, however, he is fair, consistent and knows the intent of the contract requirements, he will earn respect and cooperaton.

Welding Knowledge.—An inspector must have sufficient knowledge of the welding processes to know what defects

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are most likely to occur and where to find them. He should be familiar with characteristic weaknesses of welders and have a general knowledge of machine settings and welding techniques.

Knowledge of Drawings and Specifications.—Since the inspector must be familiar with all applicable drawings and specifications of products he is to inspect, he must be able to read and thoroughly understand blueprints which include welding and non-destructive test symbols. On many occasions decisions are made where specifications or drawings are not at hand, and the inspector must rely on memory. This means that his knowledge of the drawings and specifications must be correct and complete.

Knowledge of Testing Methods.—A number of methods of testing are at the inspector's disposal in order to ascertain whether welding is meeting quality requirements. As each of these methods has its limitations, and since it may be necessary to employ several in the inspection of a product, an inspector must know exactly what each method will show and how to interpret the results obtained.

Report Writing.—An inspector should be able to write clear and concise reports in order that his superiors will have no difficulty in interpreting his meaning, and so that he too will be able to understand his own reports when they become several months old. Reports should be concise but complete enough to be clear to a reader unfamiliar with the product inspected. In writing reports, it must be kept in mind that, although specific facts of the case are well known now, they must be included since they may not be remembered a year hence. Good report writing not only protects the inspector in the future, but helps him adhere to his policy of set standards.

Desirable Characteristics

While the following factors are not essential, they are highly desirable and a wise inspector lacking any of them will try to compensate for them through study and observation.

Welding Experience.—Actual experience as a welder is very valuable to an inspector because he is able to find defective work quickly and has a good idea of its cause. His interpretation of quality standards then will be much more practical, and he will be able to offer constructive criticisms when rejecting poor work.

Education and Training.—If an inspector has had previous training in fundamental engineering design and metallurgy he is exceedingly fortunate. However, many excellent inspectors have not had such formal education, but they have acquired a working knowledge through experience and study. The more of such knowledge an inspector possesses, the more intelligent decisions he can make, as he will be more aware of critical points and better able to emphasize quality control of important areas. Basic education in English, mathematics and drawing is very helpful in performing inspection duties such as reading specifications and writing reports.

Inspection Experience.—The attitude and point of view of a good inspector can be acquired only through inspection experience. If a welding inspector has had previous experience at any kind of inspection, he will find it very helpful in welding inspection. Those without such experience should endeavor to study the behavior of experienced inspectors, and they will find that good inspection involves a distinct way of thinking and working that should be acquired.

DUTIES OF A WELDING INSPECTOR

General

It must be understood that an inspector's primary function is that of inspecting the work being performed by the fabricator to see that it complies with the requirements prescribed by the contract. From time to time the fabricator may request advice as to changes or modifications in his manufacturing procedure. Where such changes or modifications do not conflict with the requirements of the drawings or specifications or other instructions, the inspector should cooperate in every way possible, but with the definite understanding that the fabricator has full responsibility for the final product.

An inspector should keep in touch with the activities of the fabricator's production organization, not because the fabricator may intentionally disregard certain requirements of the contract, but because errors may occur through carelessness or lack of familiarity on the part of the

fabricator. The correction of manufacturing errors is the responsibility of the fabricator, but the inspector should make certain that such errors or defects are brought promptly to the fabricator's attention, for correction at the start may often result in the production of satisfactory material which would otherwise be rejected.

The inspector should realize that he holds a position of some importance and responsibility and that he should conduct himself, both on and off duty, as a person of good character, ability and common sense. He should observe regular working hours, preferably those observed by the manufacturing organization, as well as all rules and regulations pertaining to personal conduct, safety and security established in the fabricator's plant. He should not consider himself as entitled to certain special privileges. In his dealings with the fabricator's organization the inspector should be impartial, render prompt decisions and give a tolerant hearing to the opinions of others, but he should stick to facts and not be unduly influenced by opinions.

The duties of a welding inspector will, for most types of structures, follow the general order of fabrication procedure and will relate to those details which more or less directly pertain to the welding operations:

(*a*) Interpretation of drawings and specifications.
(*b*) Verification of procedure and welder qualification.
(*c*) Checking application of approved welding procedures.
(*d*) Selection of production test samples.
(*e*) Interpretation of test results.
(*f*) Preparation of records and reports.

Interpretation of Drawings and Specifications

If possible the inspector should study the drawings and design in advance with the object of becoming familiar with the construction details, the proposed use of subassemblies, and the provisions made for welding. It is also desirable to consider the material to be used in the welded structure since certain metals often require special treatment to be satisfactorily welded.

During the course of fabrication of a welded structure, the inspector may be called upon repeatedly for interpretations of drawings and specification requirements. His ability to render clear and concise decisions in these matters based on prior study of the drawings and design will aid greatly in speeding completion of the work under contract.

Situations necessitating some deviations from drawing and detailed specification requirements may arise during the fabrication of any structure and it will be the inspector's duty, unless other approval is required, to decide whether the deviation in question can be permitted. Very often the acceptance or rejection of a large welded structure may be involved and it will be his duty, after very careful study, to decide whether or not the error can be corrected and whether the method of correction to be used will still insure a satisfactory completed product in accordance with the drawings and specifications. In all cases the inspector should exercise extreme caution in accepting deviations.

It is not always possible to include in a specification all of the detailed information necessary to provide an answer for all questions which may arise during construction. However, for those parts of the specification in which requirements are not clearly defined, it will be the inspector's duty to interpret them in a way that, to the best of his judgment, will satisfy the meaning and intent of the specification.

Verification of Procedure and Welder Qualification

One universal principle involved in specifications and codes pertaining to the fabrication of weldments is the requirements that the fabricator must prescribe the welding procedures which will be followed in producing the weldments under a particular specification or code. These welding procedures are prescribed for types, grades and thicknesses of base metal and types of joints, as determined by the design of the weldments, and should be such as to produce welded joints with acceptable mechanical characteristics in accordance with the requirements of the particular specification or code involved.

Before any production welding is done, it is the inspector's duty to verify that definite welding procedures have been established and that these welding procedures can produce welded joints in ac-

cordance with the requirements of the pertinent specifications or codes. In order to do this, the inspector must either have witnessed the welding and testing of the qualification specimens to demonstrate the sufficiency of the welding procedure, or have available authentic documentary evidence which demonstrates that sufficiency. Whenever possible, it is preferable that the inspector actually witness the tests because factual knowledge of the details of the welding procedures often affords valuable assistance in later production inspection duties.

It is also a duty of the inspector to take due cognizance of any changes that may be made in any welding procedure being used which exceed the limits prescribed by the pertinent welding procedure specification. He will see that the welding procedure specification is changed accordingly, and ascertain whether requalification of the welding procedure is required. If requalification is required, he will see that the change is not applied to production work before the necessary qualification tests have been completed and the change found satisfactory.

Codes and specifications pertaining to the fabrication of weldments usually require that all welders be qualified in accordance with prescribed procedures.* The procedure necessary to qualify welders is usually prescribed by the particular code or specification and it is the inspector's duty to verify that each welder working under that code or specification has been properly qualified. This verification is obtained either by the inspector personally witnessing each test or reviewing authentic records of tests previously made. In this connection, it is an important duty of the inspector to see that welders are employed to do work only to the extent to which they have been qualified.

Welding codes or specifications do not always require requalification of welding procedures and welders for each new contract or change of design unless some new or additional welding requirements originate thereby. It is the inspector's duty to interpret the requirements of the specification or code in this respect and be governed accordingly. Every effort should be made to avoid unecessary qualification testing in fairness to the fabricator as well as to the purchaser.

Checking Application of Approved Welding Procedures

It should be recognized that the passing of a qualification test does not, of itself, insure proper application of the qualified welding procedure. Therefore, adequate inspection is necessary to determine that the qualified procedure is being properly and competently applied. The inspector will find it advantageous to prepare a check list from each pertinent welding procedure specification for use in performing this inspection.

The practices among different fabricating shops vary due to location, equipment and experiences which have been gained by their application of welding. In all cases, however, the final result should be the same. Inspectors who have had experience in only one or two shops should not attempt to convert the fabricator with whose organization they are working, to the welding practices with which the inspectors are familiar. Should this be attempted, the result is likely to be increased cost of fabrication, confusion due to unfamiliar methods and a general animosity toward the inspector.

It is essential that the inspector be fair and endeavor to exercise sound judgment when applying visual or other inspection procedures and in passing on the acceptability of the welding. It is the inspector's responsibility to see that weldments requiring repair are correctly and properly marked to indicate the location and nature of repairs required. The system of marking used for indicating repairs should be clearly understood by the fabricator's organization as well as by the inspector in order to avoid misunderstandings and failure to make proper repairs where indicated. The inspector's responsibility does not end when he discovers and marks defects for repair. He also must pass upon the acceptability of the repaired welds.

In general, it is desirable that welding inspection operations be performed in step with the manufacturing operations set up by the fabricator.

Selection of Production Test Samples

In many types of welded fabrication

* This may not be true of machine welding, particularly where the operation is fully automatic.

certain inspection of the finished product may be performed on samples selected by the inspector from the production line. These samples may be selected at random or in accordance with some established order of frequency. In either case, the selection of these samples and the inspection and test thereof, are among the important duties of the inspector.

It may be that the selection of these samples is left to the judgment and discretion of the inspector instead of being definitely prescribed by the pertinent specification or code. In such cases the number of samples selected should not be excessive but should be sufficient to determine that the required standards are being met in production.

Certain tests or treatments may be prescribed for the samples selected by the inspector. These may include radiography, hydrostatic tests, trepanning, metallurgical examination, mechanical testing to destruction or other detailed examinations. It is the inspector's duty to see that such tests, as prescribed, are carried out properly. Various sampling, inspection and tests methods are described later in this chapter.

Interpretation of Test Results

When any of the various inspection methods or tests have been performed in accordance with prescribed requirements, the inspector must necessarily evaluate the results and decide whether they meet the specified requirements. Sometimes this decision requires careful study because it may happen that the results obtained do not meet the required standards for acceptance in every detail. In such cases a thorough study must be made of the results and of the requirements to be met before a decision on acceptance or rejection is made.

The welding inspector must make the final decisions as to acceptability of the weldment unless otherwise limited. In those cases where functioning of an item is involved in the final decision, the inspector's responsibility in that connection is usually fixed by the specification or purchaser.

Preparation of Records and Reports

Any of the work performed under a specification or code which requires inspection or tests will also require adequate records. However, whether records are required or not, the inspector should keep adequate notes of his inspection work.

Records should be prepared in such detail as conditions necessitate. It is always desirable to comment on the general character of the work, such as observance of prescribed tolerances, difficulties under which any part of the work may have been performed, and any defects found by inspection. Explanation should also be given for repairs made. The inspector should see that copies of these records go to the persons entitled to receive them and should retain a copy in his own file for future reference.

WELDMENT DEFECTS

Arc and Gas Welding

Weldment defects in arc and gas welds may be classified in three general groups: dimensional defects, structural discontinuities and defective properties. It should be obvious that all possible defects that may be encountered in welds cannot be covered in this brief discussion. Therefore, for a more complete treatment of the subject, reference should be made to the AWS *Inspection Handbook for Manual Metal Arc Welding*. Throughout this discussion it is assumed that the materials under consideration have been shown to be weldable and further that a qualified welding procedure has been used by qualified welders.

Dimensional Defects

Warpage.—Dimensional defects are largely avoidable if proper controls are exercised in the welding procedure. Warpage or distortion is generally controllable by the use of suitable jigs, welding sequences or preforming prior to welding. The exact method employed will be dictated by the size and shape of the parts as well as the thickness of the metal. Where warpage is unavoidable, it may at times be counteracted by using flame shrinking.

Incorrect Weld Size.—Deficiencies in weld size are detected by visual examination and gaging with suitable weld gages. Such deficiencies should be corrected by the use of the correct filler metal size, employment of the proper technique or the institution of such other measures prior to welding as will fulfill the necessary requirements. It is sometimes

possible to correct undersize welds by the addition of beads of weld metal.

Incorrect Weld Profile.—The profile of the individual layers of multilayer welds may have considerable effect upon the ease or difficulty encountered in depositing subsequent layers. In general, with fillet welds. A typical example of overlap in fillet welds is pictured in Fig. 2. Overlap may be generally attributed to improper welding technique or improper welding heat.

Another defect, excess convexity, tends to produce notches which lead to harmful

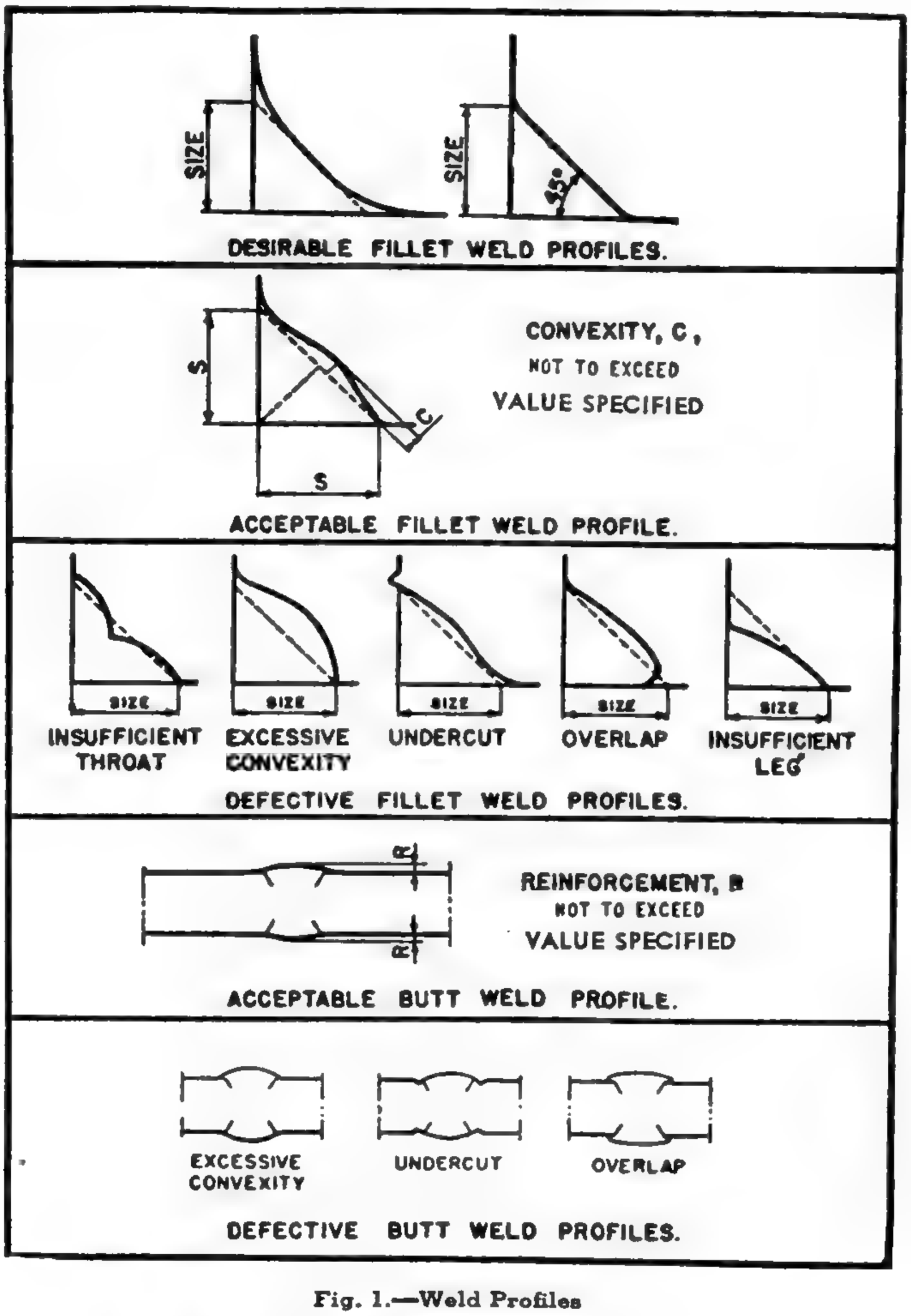


Fig. 1.—Weld Profiles

Illustrating acceptable and defective weld profiles.

procedure specifications should indicate the limits of these variables and these limits should be checked carefully to assure sound welding. Figure 1 illustrates some of the more common defects in weld profiles as well as acceptables profiles. Overlap is a defect usually associated

concentrations of stress under load. Excess convexity in multilayer welds can easily lead to slag inclusions or unfused areas. Again this defect, associated with fillet welds, is usually attributed to improper welding technique. Excess concavity is a defect also generally associated

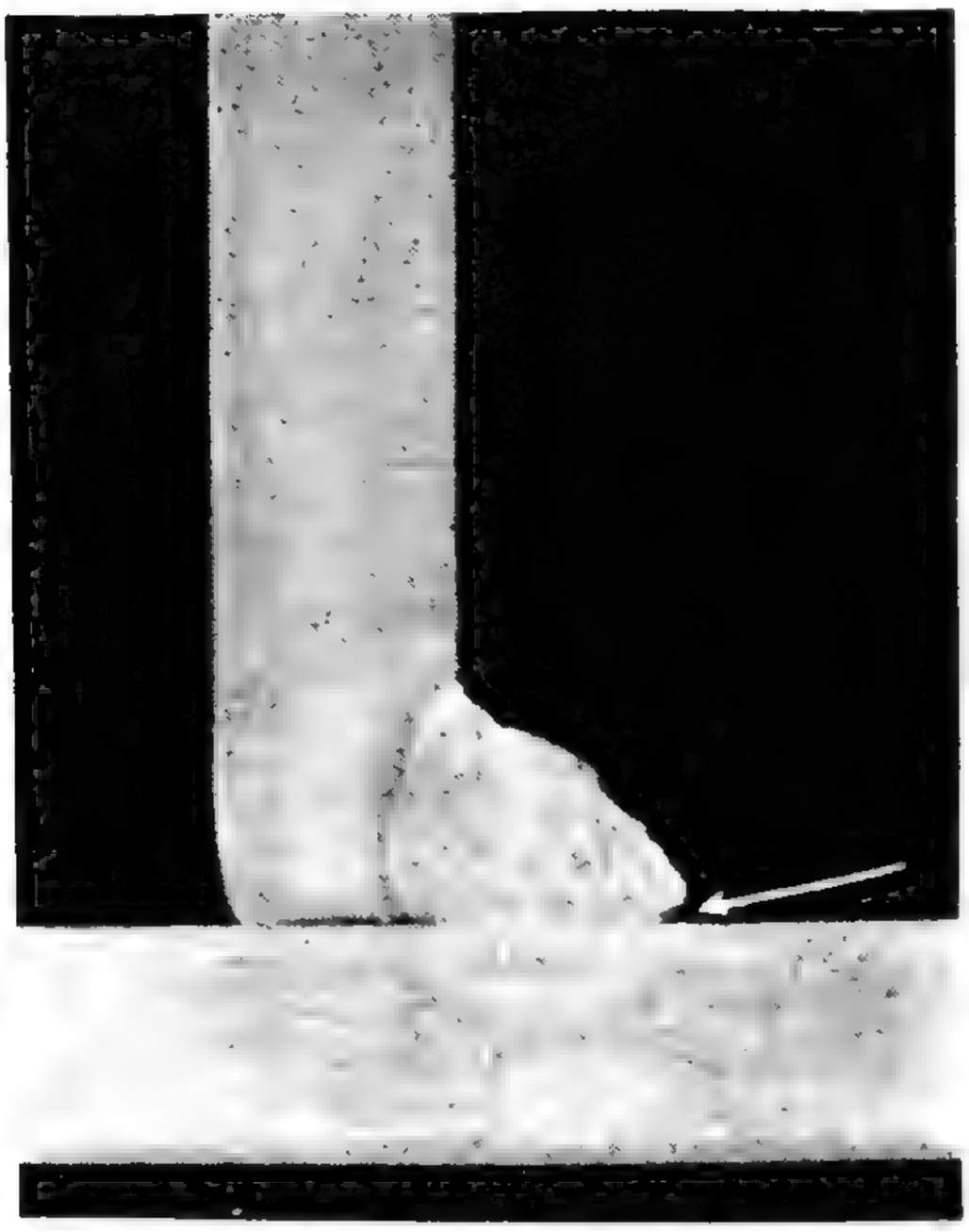


Fig. 2.—Overlap

with fillet welds. Stated simply, this merely means that the weld is of insufficient size and, in consequence, of insufficient strength. The most common source of this defect is the use of excessive welding heats which result in very fluid weld metal and a tendency to produce thin-section deposits. Excess weld reinforcement, commonly associated with groove welds, is, in effect, somewhat similar to excess convexity in fillet welds. It is undesirable since it tends to stiffen the section unnecessarily, thereby creating a notch effect.

Structural Discontinuities

Structural discontinuity is a term used to indicate those defects encountered in the weld proper including such specific items as porosity, nonmetallic inclusions, incomplete fusion, inadequate penetration, undercutting, cracking and surface defects.

Porosity.—Porosity describes a type of globular voids free of any solid material which result from the chemical reactions occurring during welding. The gases forming the voids are released during the cooling of the weld metal, and are caused by reduced solubility with falling temperature and by gases formed by chemical reactions. Employment of excessive welding heats or incorrect manipulation will generally be found to be the cause of porosity. A typical example of porosity is shown in Fig. 3. The porosity may be uniformly scattered throughout the entire weld, isolated in small groups or distributed linearly as at the root. The first condition indicates overall poor welding, the second some temporary fundamental change in welding conditions and the third is often considered a special case of inadequate penetration.

Nonmetallic Inclusions.—Nonmetallic inclusions is a term used to describe oxides and other solids sometimes encountered as elongated and globular inclusions in welds. The oxides are derived from contamination of the weld metal by the atmosphere. Slag inclusions, in arc welding, are generally derived from electrode coating materials while in gas welding they occur when fluxes are employed in the welding operations. Ordinarily such solid materials being of lower specific gravity than the weld metal would tend to float to the surface. When this cannot occur and they are trapped, they are termed inclusions. One source of such inclusions has been indicated in the previous discussion under excess concavity. These non-metallic inclusions are best avoided by use of the proper welding techniques and cleaning procedures both be-

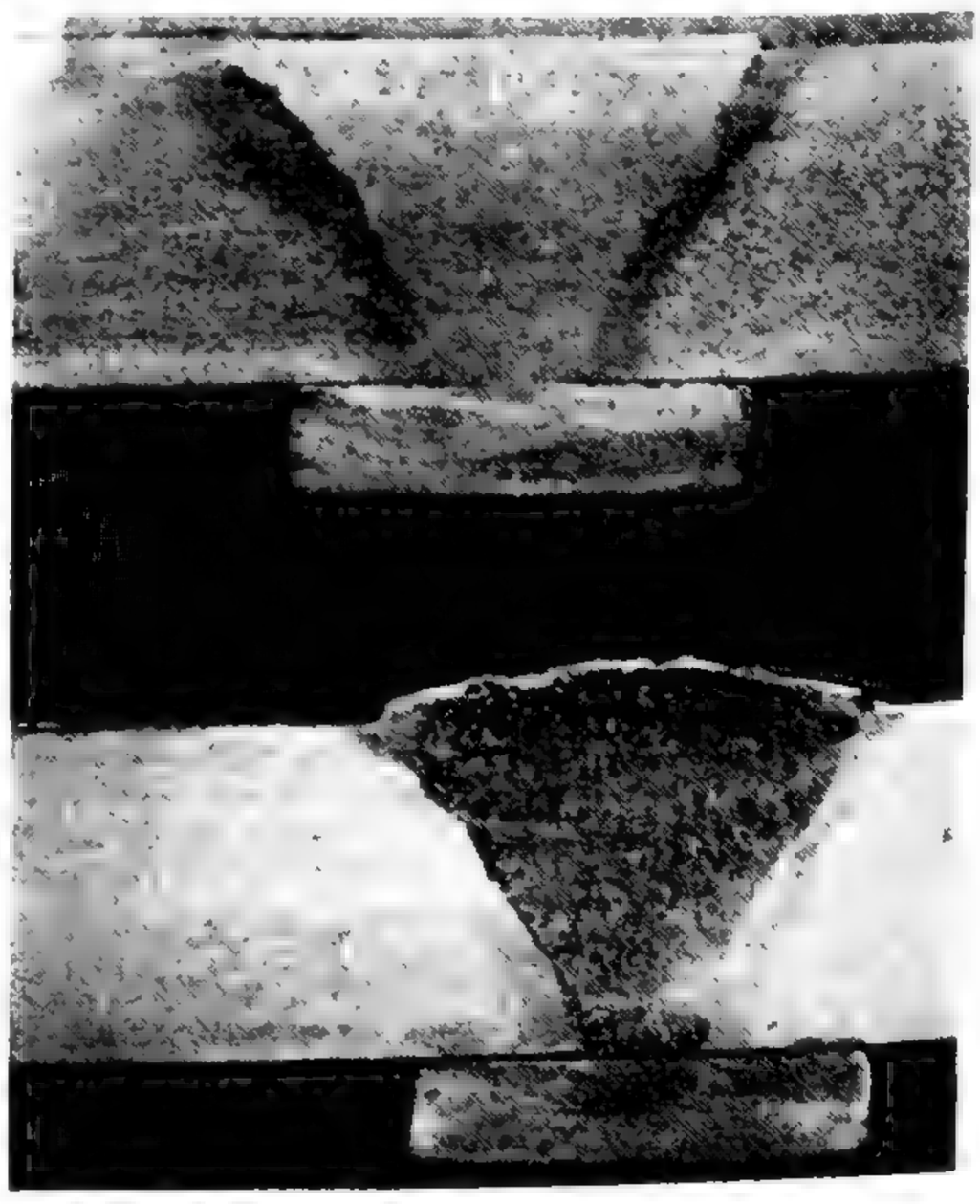


Fig. 3.—Porosity

Top view shows sound weld. Bottom view shows porous weld.

fore and during welding. The use of too large a size filler metal, particularly on the first layer or bead, is very likely to contribute to inclusions in the root area. In multilayer welding, failure to remove all slag between layers will result in slag inclusions in these zones. A typical slag inclusion is illustrated in Fig. 4.

Fig. 4.—Slag Inclusion

Illustrating fusion zone slag.

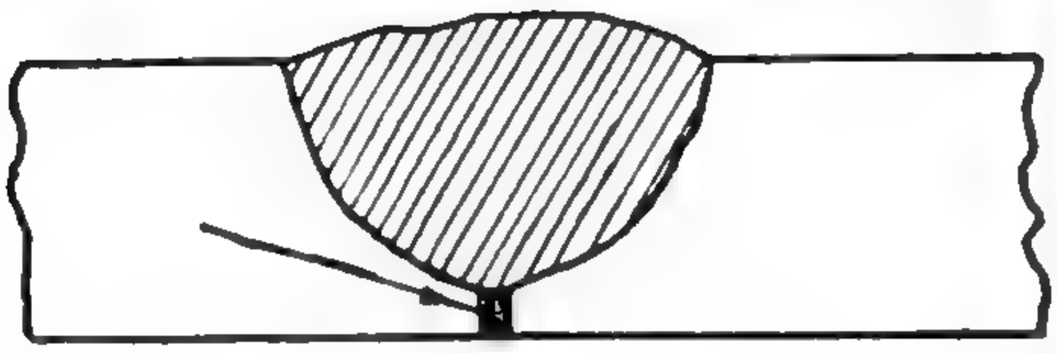
Incomplete Fusion.—Incomplete fusion is here used to indicate the failure to fuse together adjacent layers of weld metal or adjacent weld metal and base metal. A typical example of incomplete fusion in a fillet weld is shown in Fig. 5. Incomplete fusion may be caused by failure to raise the temperature of the base metal (or previously deposited weld metal) to the melting point or to dissolve, by means of fluxing, the oxides or other foreign material present on the surfaces to which the deposited metal must fuse. From this it should not be inferred that deep melting is necessary to secure coalescence, since it is only necessary to bring the surfaces of the base metal to the melting temperature to obtain metallurgical continuity of the base and the weld metals. Incomplete fusion is avoided by maintaining surfaces free from foreign materials and by using proper heat and manipulation.

Inadequate Penetration.—Inadequate penetration is a condition existing in groove welds when the deposited metal and base metal are not integrally fused at the root of the weld. If this condition is caused by the failure of the root face of a groove weld to reach fusion temperature for its entire depth, then it is, in effect, a special case of incomplete fusion. However, it may also be caused by weld metal bridging from one member to the other. Typical examples of inadequate penetration are shown in Fig. 6. This condition is most frequently caused by areas of base metal above the root reaching the molten condition before proper temperature is obtained at the root. It is, therefore, important to assure proper heat distribution so that fusion will occur uniformly throughout the root area. The use of too large a size filler metal may cause the condition of bridging, particularly in butt joints. This may be corrected by the use of the correct size of filler metal or by increasing the size of the root opening within the limits set for the size of filler metal and type of joint. Inadequate penetration may lead to cracking; in multilayer welds a crack in the first layer may well propagate through the entire welded cross section, hence it is important to insure complete penetration.

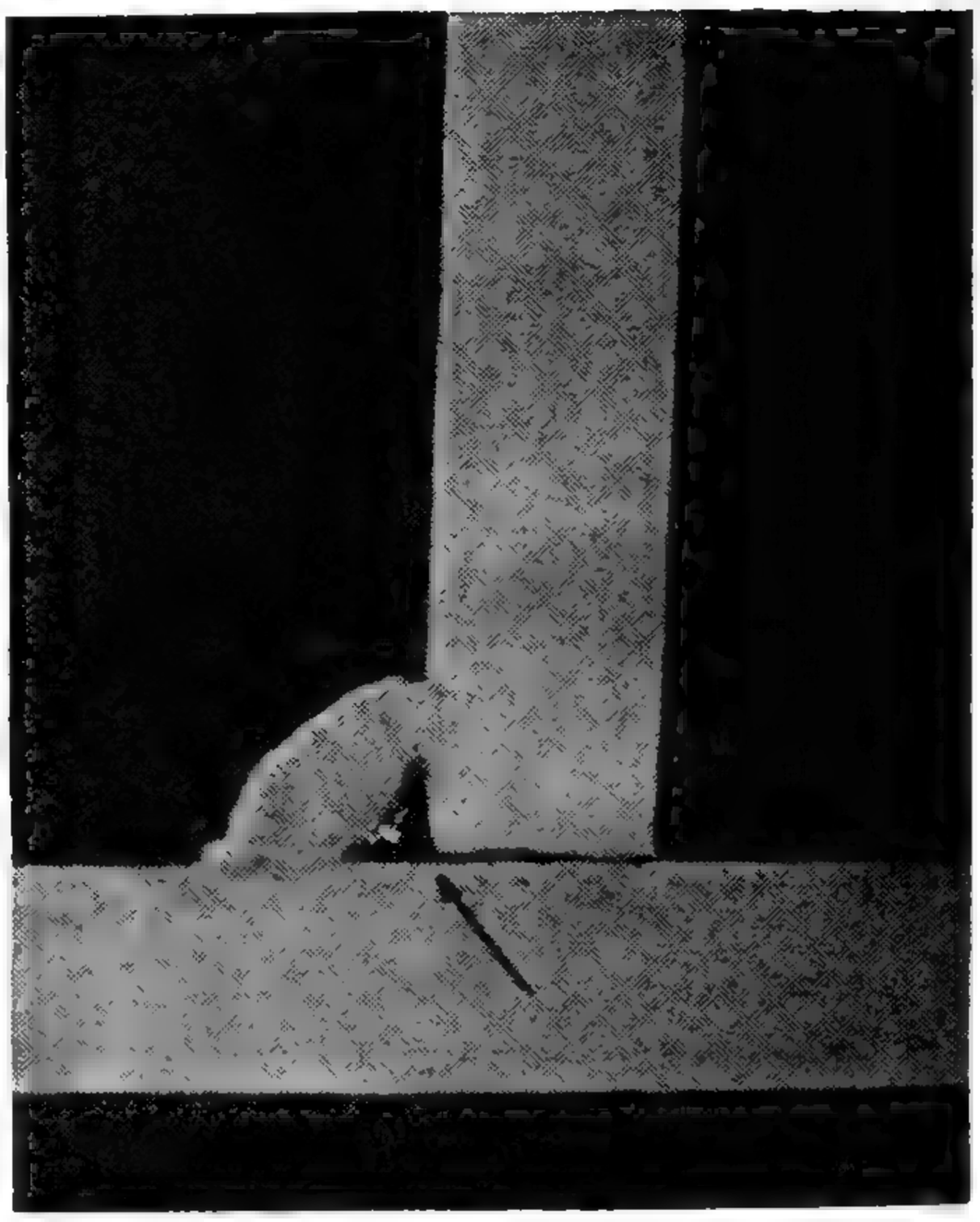
Undercutting.—Undercutting is the melting or burning away of the base metal at the toe of the weld. On multilayer welds, it may also occur at the juncture

Fig. 5.—Incomplete Fusion

of a layer with the wall of the groove. In the first case, such undercutting obviously reduces the cross section of the metal and, therefore, the strength of the joint. Undercutting in general can be attributed to faulty technique. The use of excessive welding heat is very likely to contribute to this condition. In ad-



Illustrating inadequate penetration in a groove weld.



Illustrating inadequate penetration in a fillet weld. This condition is often referred to as bridging.

Fig. 6.—Inadequate Penetration

dition faulty manipulation of the electrode (or welding rod), particularly in arc welding, may also contribute to undercutting. Undercutting the side walls of the welding groove is not necessarily a defect provided such undercutting is enlarged to permit satisfactory welding of the subsequent layers. Such an undercut, improperly treated, can lead to slag inclusions. Undercutting as encountered in butt joints is illustrated in Fig. 7, while undercutting on fillet welds is shown in Fig. 8.

Cracking.—Cracking of welded joints

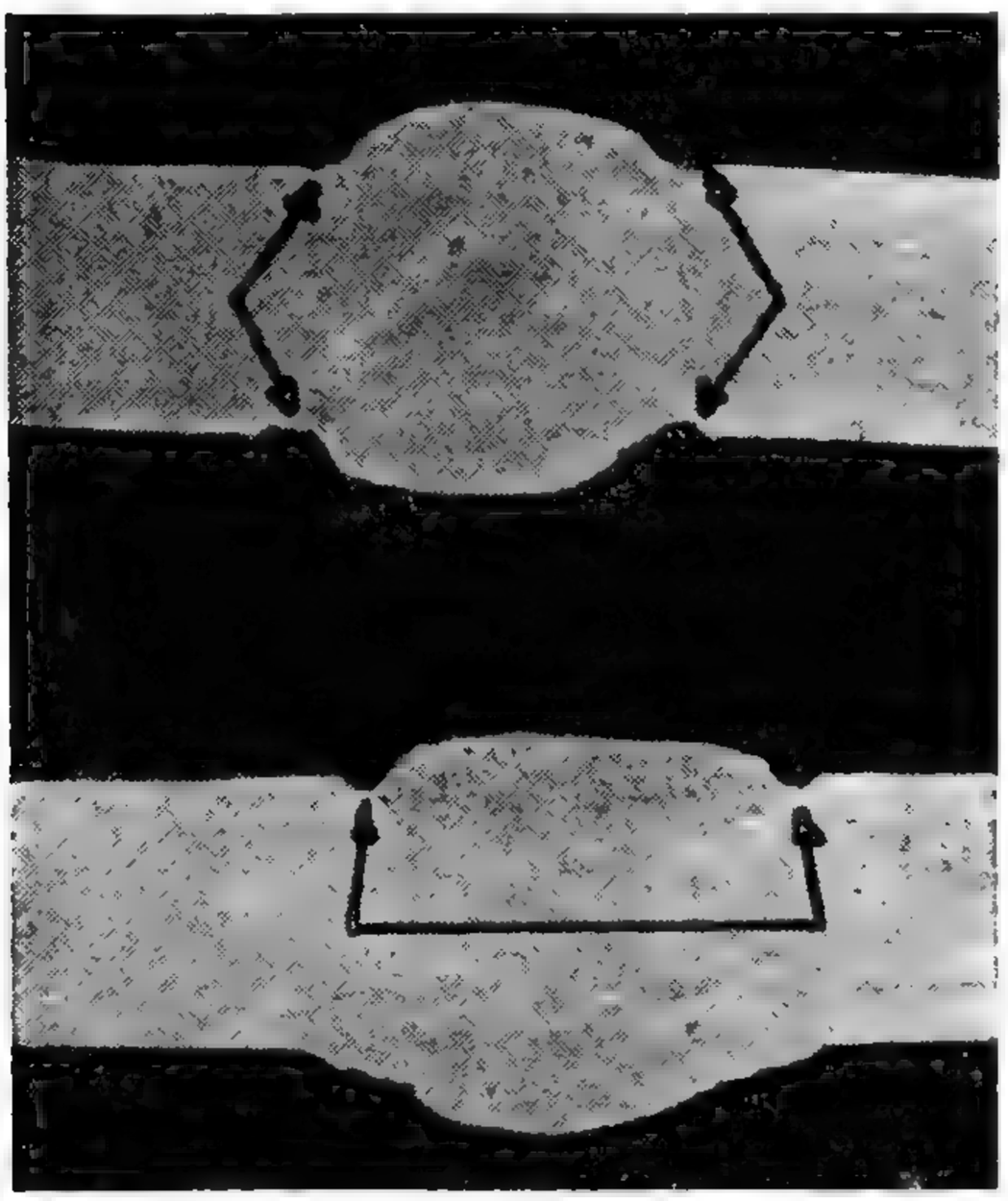


Fig. 7.—Undercutting in a Groove Weld

Fig. 8.—Undercutting in a Fillet Weld

results from the presence of localized stress which at some point exceeds the ultimate strength of the material. When cracks occur during or as a result of welding, little deformation is usually apparent because the shrinkage resulting from welding sets up multidirectional stress systems with the attendant inability of the material to sustain appreciable deformation without failure. On heavy or complicated assemblies, which may not show cracks during welding but which may crack when subjected to load, it is common practice to require stress-relief heat treatment to minimize these effects. In addition, unfused areas at the root of a weld may result in cracks if they are subjected to tensile stress, and further, these cracks will tend to progress through the entire weld on multilayer welds. Typical weld metal cracks are pictured in Fig. 9.

The ability of a weld deposit to remain intact under the stress system imposed during the welding operations is a function of the composition and structure of the weld metal. Cracking of the weld metal is likely to occur in the first layer, particularly if of thin cross section. Such cracks may continue up through subsequent layers. This cracking tendency may be corrected by increasing the thickness of the first layer, by controlling the heat input, changing electrode manipulation or reducing travel speed. Preheating may be employed to modify the stress system being imposed.

Weld metal cracks are of three types (see Fig. 9): transverse, longitudinal and crater cracks. *Transverse cracks* may in some cases extend beyond the weld into the base metal and are usually encountered in joints having a high degree of restraint. *Longitudinal cracks* may originate in crater cracks or in first-layer cracks as discussed previously. In either case they should be corrected before additional layers of weld metal are deposited. *Crater cracks* are peculiar to arc welding and may occur whenever the welding operation is interrupted. If the crater is filled in the continuation of the welding, then the cracks are generally eliminated.

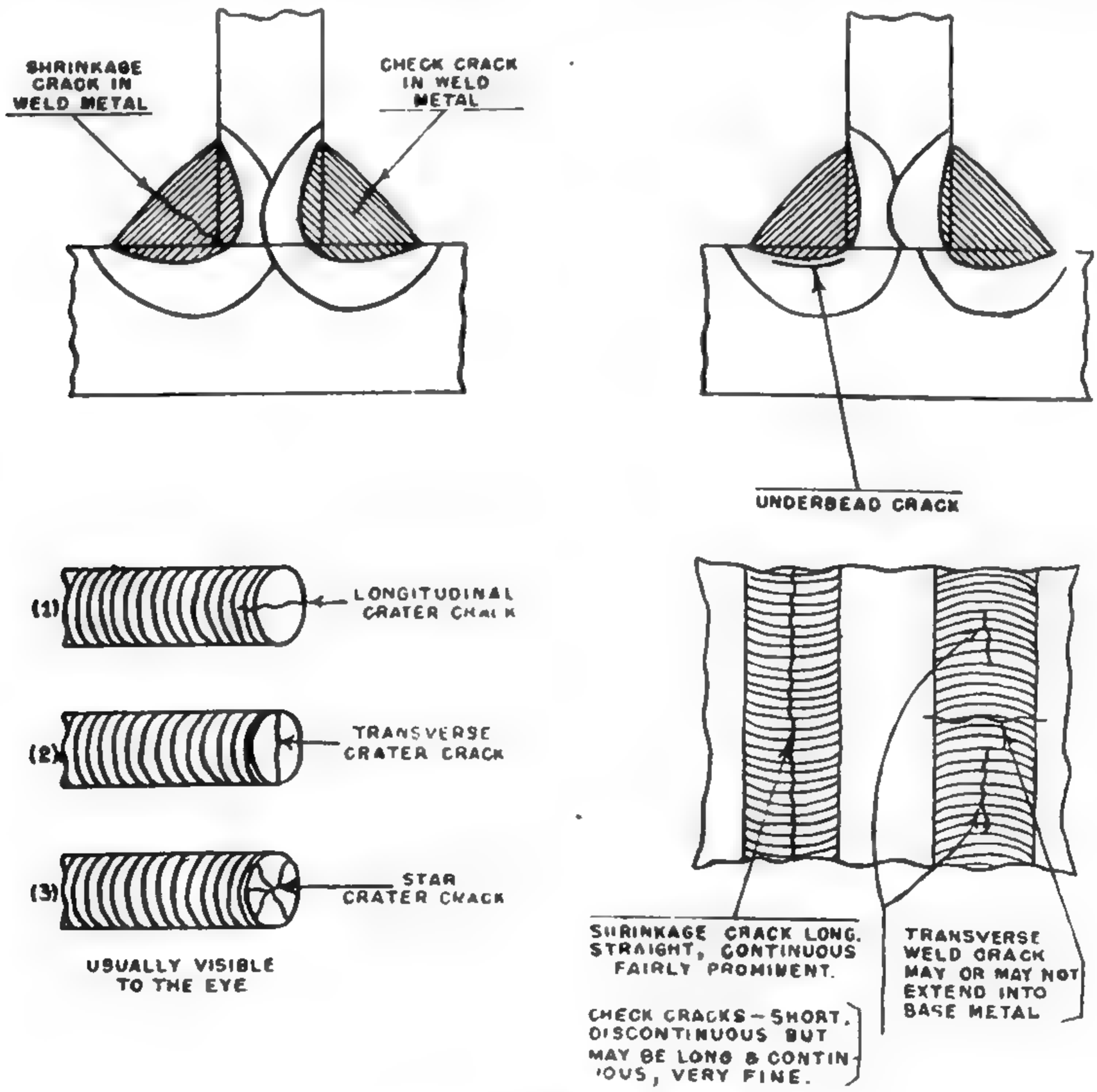


Fig. 9.—Weld Metal Cracks

If the crater is at the end of a weld and the crater crack is of the longitudinal variety, it may progress the length of the weld. Craters, and the attendant cracking, may be eliminated by manipulating the electrode to fill the craters.

Base metal cracking is generally of the longitudinal type and occurs within the heat-affected zone. Since it is almost always encountered in hardenable metals it results from the metallurgical effects produced by the thermal cycle of welding. It follows, therefore, that avoidance of base metal cracking is best accomplished by careful study of the hardenable metal to be welded and the selection of a welding procedure which will produce acceptable results. Preheating and/or postheating are almost always necessary in these procedures. In some cases, preheating may be omitted if austenitic stainless steel filler metal is used.

Another type of base metal cracking encountered with hardenable steels is termed *underbead cracking* (see Fig. 10).

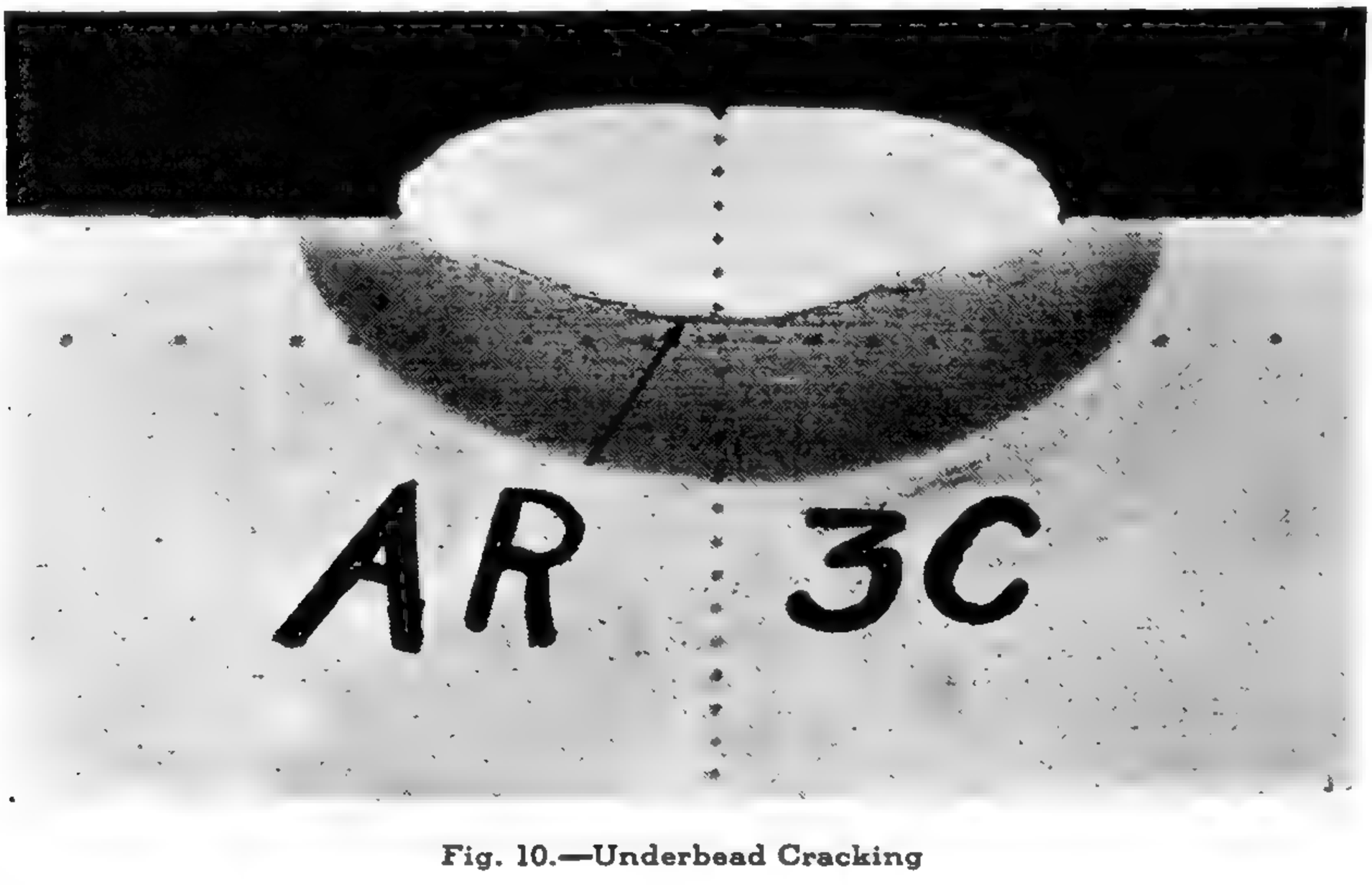


Fig. 10.—Underbead Cracking

This type of crack has been associated with hydrogen, which in the case of shielded metal-arc welding is derived from the coating of conventional types of electrodes. Preheating and postheating will help to reduce this cracking but in many types of work these treatments cannot be employed. The use of the low-hydrogen electrodes (Classifications EXX15 and EXX16) will materially reduce this cracking. When using these electrodes preheating is unnecessary up to about $^1/_2$ in. thickness and only 300 to 400°F. is necessary for heavier sections.

Surface Defects.—Surface defects in welds may be divided into two classes—surface holes and surface irregularities, the former being associated principally with the performance of the filler metal and the latter with welder performance. Surface holes are rarely present in gas welding if standard welding rods are used; if present they are probably due to improper manipulation. Surface holes in metal-arc welding may be caused by incorrect application of an electrode, or less frequently, defective electrodes. The obvious cure is to apply the electrode correctly or to secure proper electrodes. Surface irregularities (varying width and height, depressions, etc.) are not, of themselves defects of the weld. They do, however, indicate a lack of skill on the part of the welder, which is important from the point of view of appearance of the finished job.

Defective Properties.—Specific mechanical and chemical properties are required of all welds made in any given weldment. The requirements depend upon the codes or specifications involved and departure from the specified requirements should be considered a defect.

Mechanical properties which may not meet prescribed requirements include tensile strength, yield strength, ductility, hardness or impact strength. Similarly, chemical properties may be deficient because of incorrect weld metal composition or lack of corrosion resistance.

Any discussion of weld metal quality would be incomplete without considering defects possible in the base metals to be welded, since not all defects are due to improper welding conditions. The base metal requirements are controlled by applicable specifications and departure therefrom should be considered a defect. Properties which may not meet prescribed requirements include chemical composition; cleanliness (laminations, stringers); surface conditions (mill scale, paint, grease, oil, etc.); mechanical properties; and dimensions.

As a guide to the identification of defects discussed herein, Table 1, Tests for Weld and Base Metal Defects, is provided.

ample, a group of spot welds in a joint may have identical surface appearance (Fig. 11) yet, due to proximity effect

Fig. 11.—Surface Appearance of Spot Welds in 0.040-In. Stainless Steel

1st weld 2nd weld

Fig. 12.—Cross-Section of Welds in Fig. 11 Showing Shunting Effect on Size

Table 1—Tests for Weld and Base Metal Defects

Defects	Methods of Testing
Dimensional Defects	
Warpage	Visual inspection with proper mechanical gages and fixtures
Incorrect joint preparation	Visual inspection with proper mechanical gages and fixtures
Incorrect weld size	Visual inspection with approved weld gage
Incorrect weld profile	Visual inspection with approved weld gage
Structural Discontinuities	
Porosity	Radiographic, fracture, microscopic, macroscopic
Nonmetallic inclusions	Radiographic, fracture, microscopic, macroscopic
Incomplete fusion	Radiographic, fracture, microscopic, macroscopic
Undercutting	Visual inspection, bend tests, radiographic
Cracking	Visual inspection, bend tests, radiographic, microscopic, macroscopic, magnetic particle, penetrating oil
Surface defects	Visual inspection
Inadequate penetration	Radiographic, fracture, microscopic, macroscopic
Defective Properties	
Low tensile strength	All-weld-metal tension test, transverse tension test, fillet-weld shear test, base metal tension test
Low yield strength	All-weld-metal tension test, transverse tension test, base metal tension test
Low ductility	All-weld-metal tension test, free bend test, guided-bend test, base metal tension test
Improper hardness	Hardness tests
Impact failure	Impact tests
Incorrect composition	Chemical analysis
Improper corrosion resistance	Corrosion tests

Spot, Seam and Projection Weld Quality

Appearance.—The surface appearance of a resistance weld is no criterion of its strength or size. However, surface appearance is an indication of the conditions under which the weld was made. Hence, it is not always possible to judge the quality of a weld by its external appearance, and it is most important that an inspector does not employ this method for qualifying production welds. For example, a group of spot welds in a joint may have identical surface appearance (Fig. 11) yet, due to proximity effect (shunting of current through adjacent welds), all welds except the first may be greatly under strength. Figure 12 shows a decided decrease in the diameter of the fused zone of the second weld due to proximity effect only. This is easily understood in that all the welding current passes through the outside surface of both welds creating identical surface appearance for each weld. At the faying or contacting surfaces of the first weld, the contact resistance being most critical to the for-

mation of the weld nugget, all the welding current is confined to the weld area producing the desired size nugget. In the case of the second and all subsequent welds, a portion of the current is shunted through the adjacent weld or welds, hence, less than full welding current passes through the contact area producing a correspondingly smaller weld nugget. The proximity effect is more severe for closely spaced

Fig. 13.—Excessive Indentation

Table 2—Surface Conditions of Spot, Seam and Projection Welds

Type	Cause	Effect
Deep electrode indentation (see Fig. 13)	Improperly dressed electrode face; lack of control of electrode force; excessively high rate of heat generation due to high welding current; or high contact resistance (low electrode force).	Loss of weld strength due to reduction of metal thickness at periphery of weld area; bad appearance.
Surface fusion (usually accompanied by deep electrode indentation) (see Fig. 14)	Scaly or dirty metal; low electrode force; misalignment of work; high welding current; electrodes improperly dressed; or improper sequencing of pressure and current.	Under size welds due to heavy expulsion of molten metal; large cavity in weld zone extending through to surface; increased cost of removing burrs from outer surface of work; poor electrode life and loss of production time from more frequent electrode dressings.
Irregularly shaped weld (see Fig. 15)	Misalignment of work in electrodes; bad electrode wear or improper electrode dressing; bad fitting pieces; electrode bearing on radius of flange.	Reduced weld strength due to change in interface contact area and expulsion of molten metal.
Electrode deposit on workpiece (usually accompanied by surface fusion)	Scaly or dirty material; low electrode force or high welding current; improper maintenance of electrode contacting face; improper electrode material; improper sequencing of electrode force and weld current.	Bad appearance; reduced corrosion resistance; reduced weld strength if molten metal is expelled; reduced electrode life due to cumulative effect.
Cracks, deep cavities or pin holes (see Fig. 16)	Removing electrode force before thoroughly quenching welds to a temperature well below visible red heat; excessive heat generation resulting in heavy expulsion of molten metal; badly fitting pieces requiring electrode force to bring faying surfaces into contact.	Reduction of fatigue strength if weld is in a tension member, or if crack or imperfection extends into the periphery of weld area; corrosion due to accumulation of corrosive substances in recess of cavity or crack.

welds, welds in metal of low electrical resistivity and welds in metal 0.040-in. thick and up.

Normally, the surface appearance of a spot, seam or projection weld, or of a resistance-brazed joint should be relatively smooth, round (oval in the case of contoured work), free from surface melting, electrode deposit, pits, cracks, deep electrode indention or other conditions which indicate that proper electrode dressing was not maintained or that the equipment was not functioning properly. Table 2 lists some of the more common undesirable surface conditions, their causes and effects on weld quality.

Size.—The diameter of the fused area must meet the standards required by the

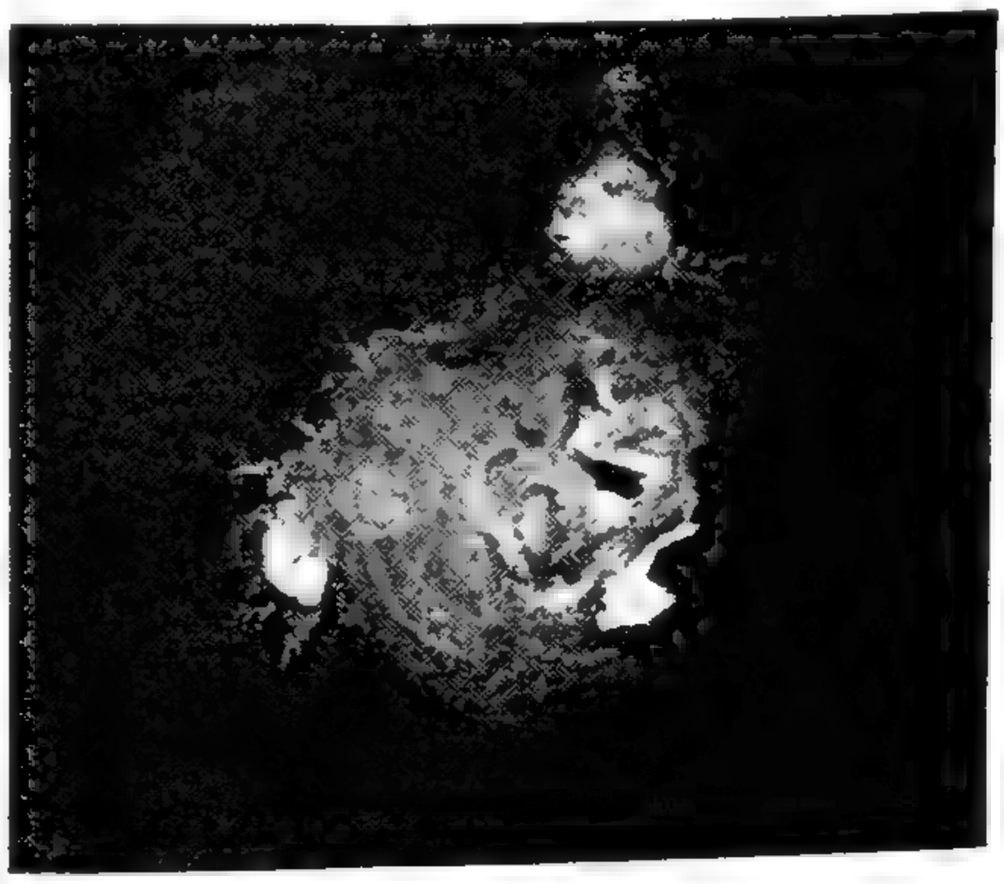


Fig. 14.—Surface Fusion Due to Surface Oxides

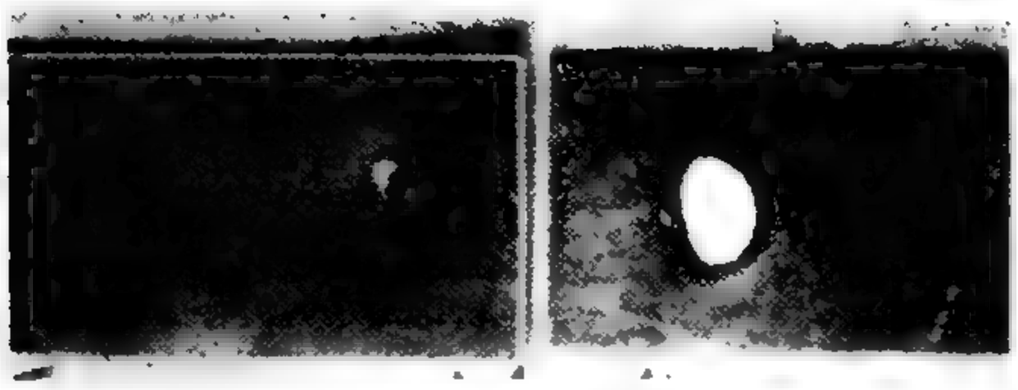


Fig. 15.—Irregularly Shaped Spot Weld

contract or design drawings. In the absence of such requirements, the values listed in the AWS *Recommended Practices for Resistance Welding* (see Chapter 16) or the following general rules may be used:

Fig. 16.—Spot Weld with Cracks and Pin Holes

1. Spot welds that are reliably reproduced under average production conditions normally have a fused nugget, the diameter of which is at least $0.8\sqrt{T}$, or a pullout button diameter at least $\sqrt{T}$ (Fig. 17) where T is the thickness of the stock in the case of two or three similar pieces, or the thickness of the thinner piece in the case of two dissimilar thicknesses. In cases of four or more equal thicknesses, the diameter of the fused nugget should be at least T. In cases of three or more dissimilar thicknesses special consideration must be given to the size of the fused area.

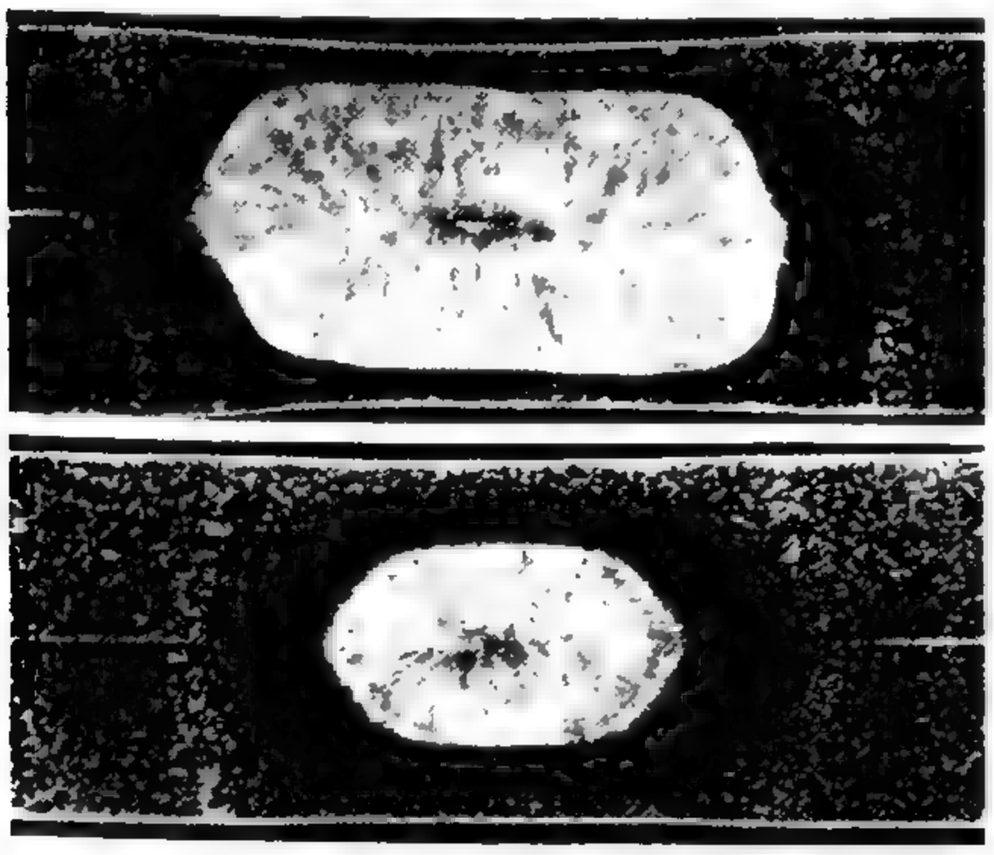


Fig. 17.—Proper and Insufficient Weld Size

Top—Normal weld nugget in 0.075-in. steel. Bottom—Undersized weld nugget in same plate.

2. Seam welds (pressure tight) should overlap 25% or more of the longitudinal dimension. The width of the fused area should be at least $0.8\sqrt{T}$ (Fig. 18), where T is the thickness of the thinner piece of a two-piece pile-up. For pile-ups of more than two pieces, special consideration must be given to the width of the fusion zone.

3. Projection welds should have a fused diameter equal to or larger than the original projection diameter. Some standards require the same diameter weld nugget for projection welds as for spot welds.

4. Brazed joints, to develop the strength of the base metal, should have a lap equal to YTW/L, where Y is the design safety factor, T and W are the tensile strength and thickness of the base metal, respectively and L is the shear strength of the brazing alloy. The thickness of the brazing alloy in the finished joint should not exceed 0.002 to 0.003 in., as the strength of the joint drops rapidly with increasing thickness.

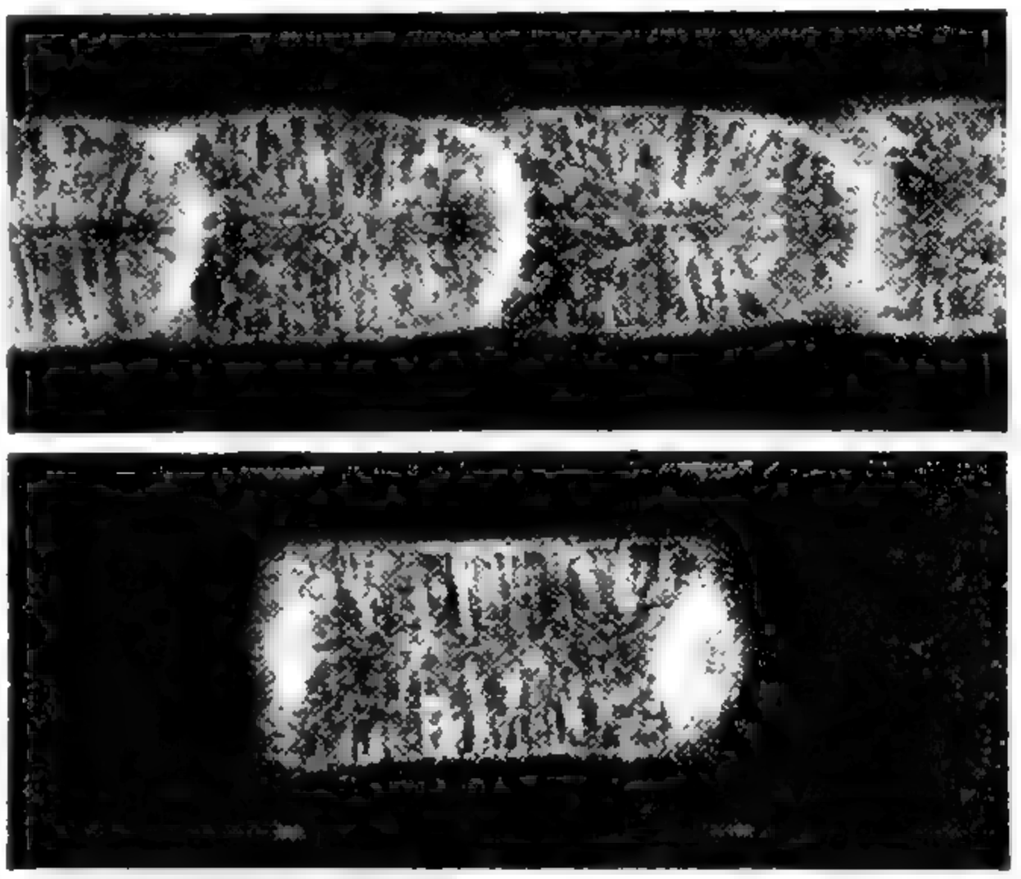


Fig. 18.—Longitudinal and Cross Sections of Proper Size Seam Weld

There also is a maximum limit to the size of a spot, seam or projection weld. This limitation results more from the economics and practical limitations of producing a weld than from the laws of heat generation and dissipation which limit the minimum size of the weld. It becomes impractical to make a weld of $^1/_2$-in. diameter in metal 0.060-in. thick, since the size of the overlap or flange width becomes excessively large for good design or economy of material. Also the electrode diameter, tool, transformer and control capacities increase to an amount which overcomes the advantages of resistance

welding to other methods of fabrication. The exact maximum weld diameter cannot be specified here, but each manufacturer should establish this limit in accordance with his existing welding conditions.

Indentation.—It is often desirable to produce so-called invisible welds. This may be approximated if all factors are closely controlled. In order to attain the best results it is necessary to understand the most important factor, that of heat shrinkage. When the work is heated, Fig. 19, it tends to expand in all directions, but due to the pressure exerted by the electrodes, any vertical expansion is immediately forged out, with the result that all of the expansion takes place in the horizontal plane, usually causing a slight ridge as shown in *A* in Fig. 19. In cooling, the contraction takes place along the lines of least resistance, or almost entirely in the vertical plane, which results in a concave surface as shown exaggerated in Fig. 19. This is not to be confused with electrode marks, where the electrode imbeds itself into the work due to improper machine settings and control. The actual depth of the depression is very small, usually not over a few thousandths of an inch, but with some types of finishing, such as high gloss enamels, it is very noticeable, especially under certain lighting conditions. It is impossible to eliminate these weld marks, but they may be materially reduced by proper control of the welding variables, that is by making the welds in short current-time cycles, thereby minimizing the conduction of heat beyond the weld zone.

Excessive indentation of spot, seam and projection welds is characteristic of welds made with too great a heat generation in the weld area, usually accompanied by expulsion of molten metal. The common causes of this are high welding current, low electrode force, undersize electrode contacting area, improper alignment of electrodes on the work, dirty or scaly metal surfaces, too long a time of current flow and improper mating surfaces.

Strength and Ductility.—Weld strength should be specified as a minimum value in the contract applicable to the job. Since spot welds are usually designed to carry shear loads, the specified value should be expressed as the *tension-shear strength*, or the *weld strength*. The standard tension-shear test, explained in more detail under Methods of Test, is the accepted method of obtaining this value. It is important, when evaluating a production weld by means of this test or any of the other methods of test, that the test be made under conditions identical with those

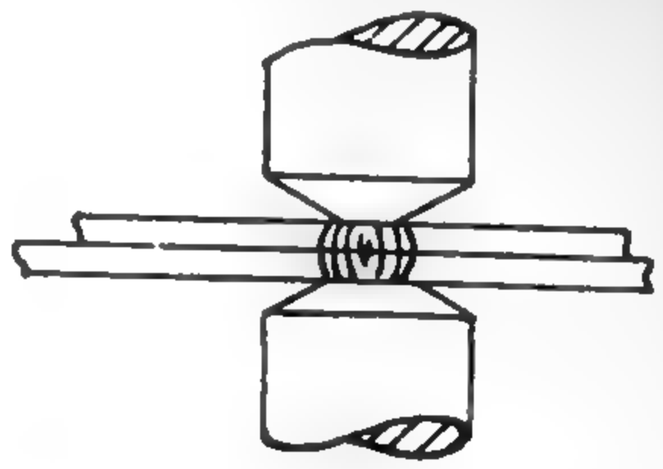


Fig. 19.—Effects of Heat Shrinkage on Spot Welds

used in production, such as the various machine settings, size and shape of electrode face, and metal thickness, finish, temper and contour. In the absence of contract requirements or an acceptable set of standards, the strength values given in the AWS *Recommended Practices for Resistance Welding* may be used. It is important to note here that weld strength in a given thickness is proportional to the diameter of the fused zone, and since the minimum and maximum diameters of the fused area are limited for reliable welding, the minimum and maximum strengths are also limited. Hence, it is not sound practice to specify weld strengths which are less than those established by the minimum fused area (see discussion, Weld Size) or greater than approximately 50% of the values given in the AWS *Recommended Practices for Resistance Welding.*

The ductility of a resistance weld is determined by the thickness and composition of the base metal and the effect on this composition of exceedingly rapid cooling from high temperatures. Figure 20 shows the fracture of a highly ductile weld and Fig. 21 shows the same for a brittle weld. The usual method of determining ductility of metals is to measure the elongation of a standard test specimen that has been stressed to its breaking point. Also, the various types of impact testing are a measure of ductility under shock loading conditions. Unfortunately, in the case of a resistance weld, these

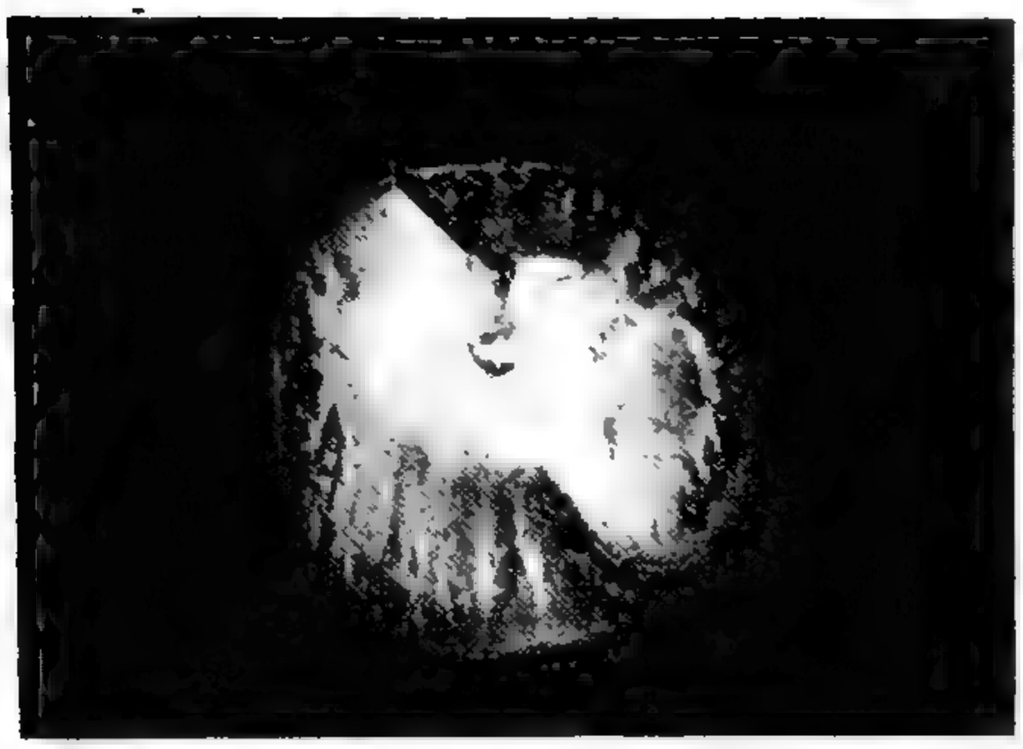


Fig. 20.—Tension-Shear Fracture of a Ductile Spot Weld

methods of measuring ductility cannot be employed, hence, there are no quantitative data for this mechanical property. The nearest thing to ductility measurements is the hardness test, since the hardness of a metal usually is an indication of its ability to be deformed, that is its ductility. For a given alloy, ductility usually decreases with increasing hardness but different alloys of the same hardness do not necessarily possess the same ductility.

Another method of indicating the ductility of a spot or projection weld is to determine the ratio of the tensile strength to the tension-shear strength of the weld. A weld of good ductility has a high ratio, a weld of poor ductility has a low ratio.

There are precautions and practices that can be taken in production welding that will minimize the hardening effect from resistance welding. Some of these are: longer time of current flow; preheating the weld area by passing a preheat current through it before the weld current to retard the rate of cooling; tempering the weld zone and heat-affected zone by passing a postheat current at some interval after the welding current, in order to elevate the weld to the tempering temperature range; and furnace annealing or tempering the welded assembly.

Fig. 21.—Tension-Shear Fracture of a Brittle Spot Weld

Penetration.—Penetration is the depth to which the fusion extends into the outside pieces and is expressed as a percentage of the thickness of the outside piece. Theoretically the penetration of a spot, seam or projection weld need only be a few mils in order to produce a sound weld with the minimum amount of heat. However, under normal production conditions, the heat generated at the faying surface of the work must be of much greater magnitude in order to obtain welds of uniform

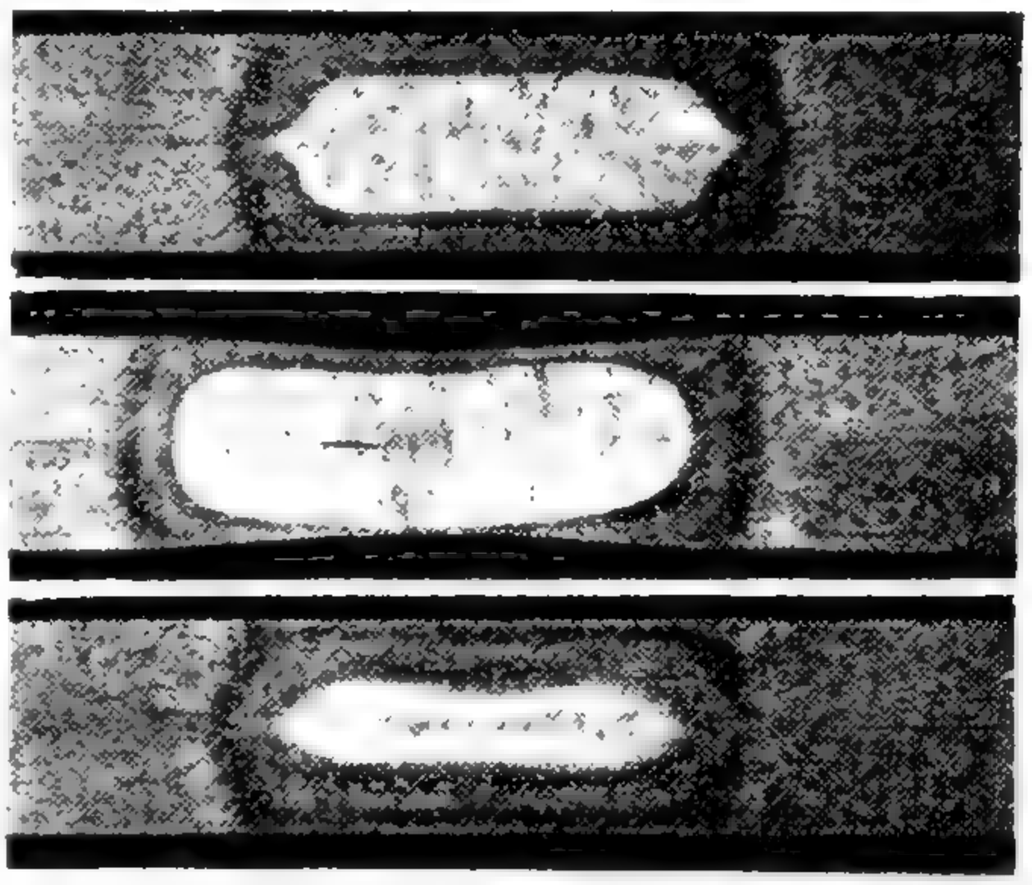


Fig. 22.—Penetration in a Spot Weld

Top—Normal penetration. Middle—Almost 100% penetration. Bottom—Less than 30% penetration

area or strength. Therefore, the minimum depth of penetration generally accepted is 30% of the thickness of the outside piece. If the penetration is less than 30%, the weld is said to be *cold*, that is, the heat generated in the weld area is so small that normal variations in current, time, electrode force, etc., will cause undesirable changes in weld strength, or even no weld at all. Figure 22 shows excessive penetration, normal penetration and insufficient penetration.

The depth of penetration into each outside piece should be approximately equal for pile-ups of equal or nearly equal thicknesses. For pile-ups of greatly dissimilar thicknesses, thickness ratios of 3 or 4 to 1, the actual depth of penetration

into the heavier piece need be only equal to that of the thinner piece.

Internal Defects.—Internal defects are any metal discontinuities in the heat-affected zone. These discontinuities include cracks, porosity or spongy metal, large cavities, and inclusions in the case of some coated metals. Generally speaking, these defects have no detrimental effect on the static strength or the fatigue strength of a weld, when located in the central portion of the weld nugget, whether they extend through to the outside surface or not. (Figure 23 shows the location of a fatigue failure.) The stresses in a spot weld are practically zero in the central portion of the weld nugget, but are highly concentrated at the periphery of the weld. Therefore, it is extremely important that no defects occur in the periphery of the weld.

Fig. 23.—Fatigue Crack in a Spot Weld

Practically all spot, seam and projection welds in metal thicknesses of the medium and heavy gages (approx. 0.040 in. and heavier) have a shrinkage cavity in the center of the weld nugget (see Fig. 24). This cavity is less pronounced in some alloys than it is in others, due to the difference in forging action of the electrodes on the hot metal, and the shrinkage characteristics of the alloy. In no case should this cavity be classified as an internal defect. However, the cavity that results from heavy expulsion of molten metal (see Fig. 24) may consume a very large part of the fused area and must be considered a defect. A certain percentage of expulsion cavities are to be expected in most production welding, hence, the job specification should accept a limited amount of them on the grounds that they normally do not impair the joint strength. Heavy expulsion of molten metal is a result of improper welding conditions, therefore, it is necessary to limit the number of such welds which can be accepted.

Internal defects in spot, seam and projection welds are generally caused by low electrode force, high current or any of the other conditions which produce excessive weld heat. They are also the result of removing the electrode force too

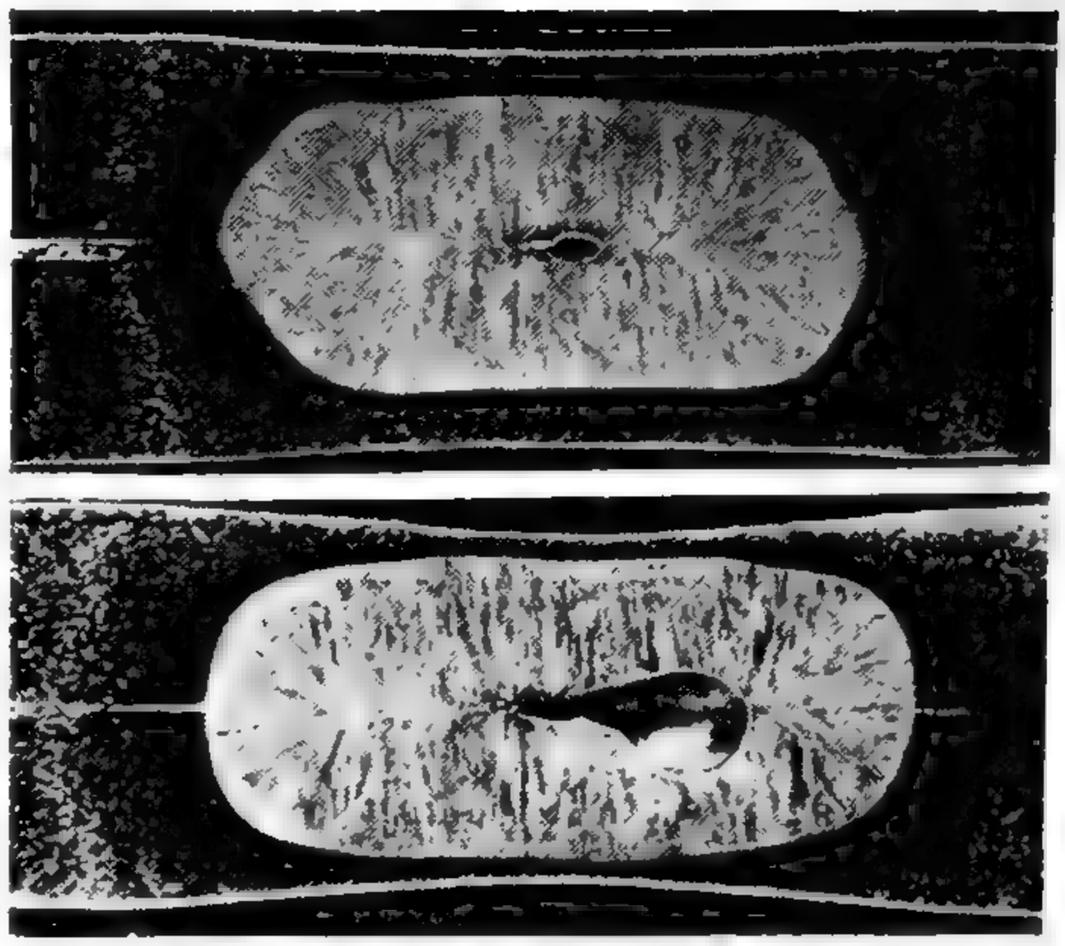


Fig. 24.—Cavities in Spot Welds

Top—Small shrinkage cavity. Bottom—Large cavity due to metal expulsion.

soon after the current flow, thus preventing the proper forging of the ingot on cooling (particularly true of high-speed seam welding or roller spot welding.) Internal defects in resistance brazing are generally caused by improper composition and application of flux, improper preparation of the joint surfaces or uneven distribution of current and electrode pressure.

Expulsion.—Expulsion of molten metal (Fig. 25) is indicative of improper welding conditions. Some of the more common causes of expulsion are: too great a rate of heat generation resulting from excessive current, insufficient pressure, undersized electrode contacting area and dirty or scaly metal surfaces; the molten zone growing beyond the limits of the confining contact area under the electrodes resulting from poorly fitting pieces, misalignment of the tool on the work, too long a time of current flow and improperly dressed electrodes or electrodes

Fig. 25.—Excessive Expulsion

of improper size. The ill effects resulting from expulsion are:

1. Bad appearance and deep surface indentation.
2. Large cavity in the weld ingot that may or may not extend through to the outside surface.
3. Reduction in weld strength due to large cavity and the fact that nugget growth usually is stopped when expulsion starts.
4. Expelled metal may extend into the area of the next weld to be made, causing that weld to expel molten metal.
5. Excessive electrode wear which becomes progressively worse when expulsion occurs between electrode and the work.

Sheet Separation.—Sheet separation (Figs. 26 and 27) is the pulling apart of the faying surfaces of a spot, seam or projection weld, due to the expansion and contraction of the molten metal and the forging effect of the electrodes on the hot metal. This must not be confused with the separation of the faying surfaces due to poorly fitting parts prior to welding. The amount of separation varies with the thickness of the stock increasing with increasing thickness. A spot weld in

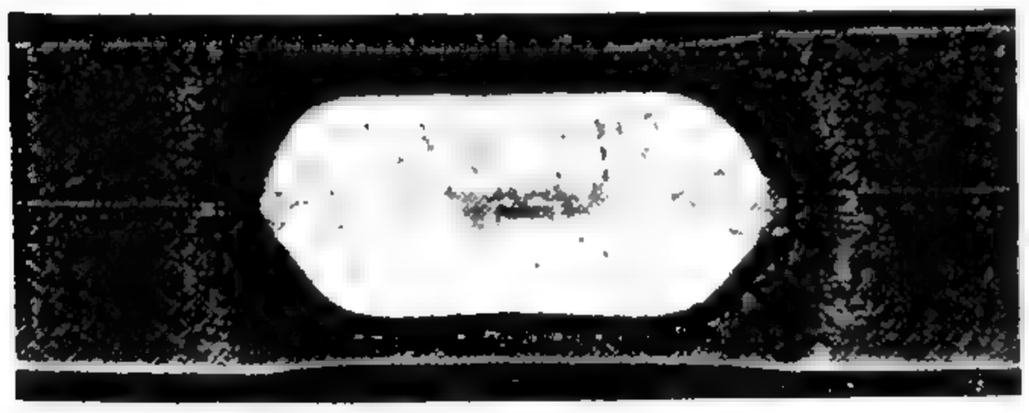


Fig. 26.—Normal Sheet Separation

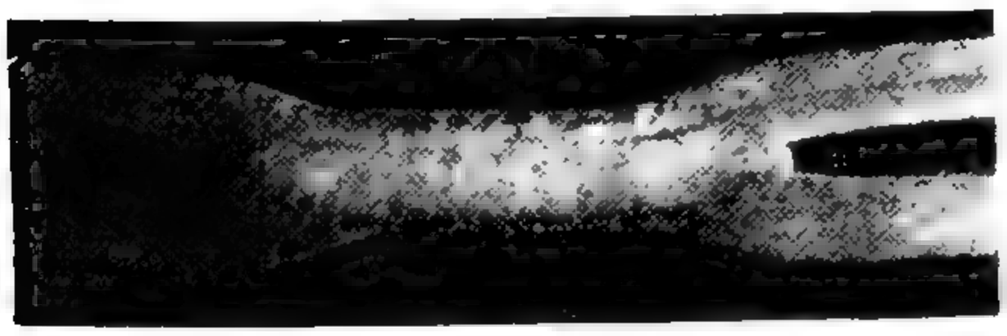


Fig. 27.—Excessive Sheet Separation

0.200-in. stainless steel will separate the sheets at the weld from 0.006 to 0.013 inch. Separation can be minimized by employing the proper welding conditions such as those set forth in the AWS *Recommended Practices for Resistance Welding.*

Misaligned electrodes will cause excessive sheet separation particularly on one side of the weld. Sheet separation will always occur in heavier gages, 0.060 in. and up. Separation is undesirable in that it increases the bending moment on the joint when stressed in shear and increases distortion of assemblies making it difficult to fit subassemblies into the final assembly.

Corrosion.—Care must be exercised when resistance welding an unstabilized stainless steel that the time at welding temperature is as short as possible in order to prevent carbide precipitation which reduces its resistance to corrosion. Figure 28 shows the carbide precipitation zone in a weld of recommended time of current flow. Figure 29 shows the carbide precipitation zone in a spot weld em-

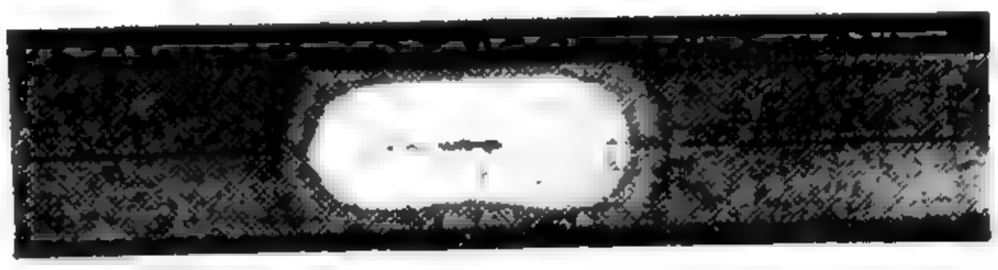


Fig. 28.—Slight Carbide Precipitation

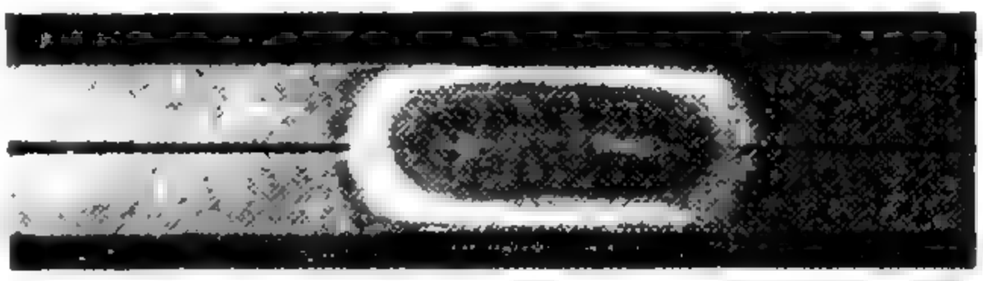


Fig. 29.—Excessive Carbide Precipitation

ploying a time of current flow longer than that recommended. (For recommended welding times reference is made to the AWS *Recommended Practices for Resistance Welding.*) Resistance brazing stainless steels that do not contain the stabilizing elements, columbium and titanium, is not recommended, since the brazing temperature is in the carbide precipitation temperature range. Electrode pickup on aluminum and its alloys will reduce their resistance to corrosion. It is impractical under production conditions to spot, seam or projection weld coated steels without breaking the protective coating on the outside surface. A simple chemical test to determine whether or not the protective coating on steels has been broken is as follows:

1. With a glass rod apply a drop of dilute (5%) solution of sulfuric acid.
2. Immediately after step (1) with a glass rod apply a dilute (5%) solution of potassium ferricyanide.
3. Immediately after step (2) the solution will turn a deep blue color where the protective coating has been removed or broken. If the solution does not turn blue, the coating has remained intact.

4. Wash thoroughly with running water immediately after testing to remove the acid.

Flash and Upset Weld Quality

Appearance.—Inspection of the surface appearance of the original metal around a flash weld will reveal gross errors in welding technique such as surface burns or *die burns,* cracks, gross misalignment and slippage of work-pieces during welding. When the loose metal or flash is removed from the weld, surface examination will generally reveal the amount of upset, the difference in upsetting characteristics between the different types of steel, if two different types are being welded to each other, the slope of the upset metal, and uneven heating during the welding operation. Only the trained eye can judge by visual examination whether a flash or upset weld is poorly made or has the expected satisfactory strength. It is necessary to watch the weld being made and visually examine the surface to properly judge the welding technique, which judgment can only be relied on and developed by examining the mechanical test results.

Surface burns or die burns result from several technique faults and are generally confined to the area immediately around the edge of the electrodes or dies. The basic cause is concentration of welding current in small areas instead of entering the part uniformly. This can be remedied by improving or enlarging the contact area of the work-piece with the welding electrode. If this fails to completely eliminate the burns, the welding electrode composition should be changed to a copper alloy having a higher electrical conductivity. In some cases it may be necessary to rearrange the welding machine construction so that current enters the work-piece from each clamping electrode instead of from only one as is common on most flash-welding machines. If the work-pieces are pitted and marked in the area where they are clamped in the electrodes it is desirable to increase the clamping force but the surface of the work-pieces should first be cleaned of dirt, scale, grease, etc.

Cracks.—Cracks are caused by an excessive quenching rate for the composition of the steel being welded. They can generally be avoided by preheating the work-pieces before welding; postheating the pieces immediately after welding; or reducing the quenching rate by immediately inserting the welded part into a furnace or slow-cooling agent such as lime, asbestos, feathers, etc.

Misalignment.—Misalignment is much more serious than appreciated by the average operator. The best weld results when the two work-pieces forge directly into each other using the upsetting force to make a complete bond over the matching weld surfaces. Misalignment prevents the upsetting force from acting over the entire weld area and produces a section of the weld which has not been forged properly, resulting in low weld quality. The greater the degree of misalignment, the greater the tendency of the work-pieces to slide past each other instead of forging with each other, resulting in unpredictable weld quality. If welds are continually misaligned, although the alignment before welding with work-pieces clamped in the welding electrodes is good, either the clamping fixture construction is not rigid enough or the final electrode opening is too large, allowing the metal behind the weld to become too hot and to lose its rigidity when the upsetting force is applied. Alignment can generally be improved by decreasing the final electrode opening.

Slippage.—Slippage of work-pieces occurs during the forging or upsetting action. It results in unpredictable weld quality. Slippage marks are visible on the work-pieces as short indented lines in the area where the clamping electrodes contact. To prevent slippage the clamping force must be increased or the work-pieces backed up by suitable means.

Upset.—Upset welds are generally characterized by large upsets having a gradual slope to the upset metal. Flash welds are characterized by generally smaller upsets having a sharper slope to the upset metal indicating a sharp temperature gradient.

For both flash and upset welding the synchronization of the upsetting force and heating period is of the utmost importance to good welding. Welds made with insufficient force contain porosity and inclusions and have widely varying strength and impact properties. Excessive upsetting force will cause excessive disturbance of the flow lines of the metal and although satisfactory tensile strength may be developed such welds will usually have poor

bending properties and poor impact resistance.

The amount of upset must be sufficient to cause a completely bonded weld and not indicate any surface void at the weld after the upset metal has been removed. In addition, the internal structure must be free of voids, porosity or traces of cast metal structure showing incomplete expulsion of molten metal.

When welding steels of radically different chemical compositions and forging properties at elevated temperatures, more uniform upsetting of each work-piece can be obtained by increasing the initial extension of the work-piece having greater resistance to forging while decreasing the initial extension of the other work-piece. In some cases it may actually be necessary to preheat the work-piece which is more difficult to forge before making the flash weld.

Non-Uniform Heating.—Non-uniform heating is characterized by irregular oxide discoloration around the weld. It results from non-uniform current distribution, improper welding electrode contact and improper fixture and electrode design for the job being welded. It is most serious when welding thin-walled tubular sections and thin, flat sheets. Non-uniform heating is also caused by improper welding technique. The flashing action should start without the work-pieces touching solidly and continue smoothly until the upsetting period. If the parts touch solidly during flashing thereby preventing continuance of the flashing action, the work-pieces will be overheated and unevenly heated. To prevent this condition the secondary voltage must be raised, the flashing speed reduced or the rate of platen travel changed by changing the flash-off cam contour. If the work-pieces do not start to flash properly it may be necessary to reduce the initial contact area by beveling one or both work-pieces.

Size and Penetration.—Flash or upset welds should be made with work-pieces having the same cross-sections at the weld so that the weld takes place over the entire cross-section. A cross-sectional etch test of a weld should indicate a heat-affected zone on each side of the weld, an absence of cast structure, a diversion of flow of the fiber near the weld and normally a white line the cause of which is yet a matter of conjecture; it is commonly attributed to decarburization, dissolved oxygen, complex metal chemical structures resulting from impurities in the metal, etc. A flash or upset weld is basically a forged structure making it different from welds made by other resistance-welding processes. The heat-affected zone varies in depth because of the speed of welding, the area and thickness of the material welded.

Strength and Ductility.—Flash welds in non-hardenable steels, with the exception of cold worked, non-hardenable alloys and precipitation-hardening alloys that become annealed in the weld zone when quenched from a high temperature, should develop practically the strength of the base metal when tested under static load. Flash welds in hardenable alloys which are to be further heat treated to insure uniformity in and around the weld zone should develop nearly base metal strength under static load up to heat treatments resulting in 150,000 psi. ultimate strength. For heat treatments resulting in base metal ultimate strengths between 150,000 and 220,000 psi., the weld strength will vary between 80 and 100% of the base metal ultimate strength under controlled welding conditions. The higher strengths are more easily developed in welds having cross-sectional areas less than one square inch.

Welds that have not had the extruded flash or upset metal removed will develop maximum strength because of the increased cross-sectional area at the weld. The degree of ductility of a flash or upset weld compared to the ductility of the base metal will depend upon the response of the alloy to relatively rapid cooling from high temperatures. For those applications in which the material composition is air hardening, some benefit from post-heating may be gained in reducing cracks resulting from residual stresses and excessive weld hardness. Simple stress relief by using a gas torch or slow cooling after welding may be adequate for steels of less hardenable nature. To insure consistent results, especially in hardenable steels, furnace treatment is recommended. Furnace treatment or normalizing is practically always required for high quality joints in air- or oil-hardenable steels.

Internal Defects.—The weld plane area of a flash or upset weld must be free from porosity, excessive number of inclusions, oxides, cast structure metal and cracks

which are a result of improper welding technique.

Corrosion Resistance.—When flash or upset butt welding austenitic stainless steels, it is sometimes necessary to anneal after welding by heating to 1900 to 2100°F. and cool rapidly enough to prevent carbide precipitation. The cases that do not require this heat treatment are stabilized steels (those containing columbium or titanium); material under 0.062-in. thick unless the corrosion conditions are extremely severe; material having a carbon content 0.08% and under unless the corrosion conditions are extremely severe.

The purpose of this heat treatment is to redissolve the chromium carbides that precipitate on either side of the weld in an area between the weld and the electrode which is in the carbide precipitation temperature range (900 to 1500°F.) during the heating and cooling cycle of the weld.

VISUAL INSPECTION

General

Visual inspection is usually defined as examination by eye, either with or without the aid of low magnification (10× or less). It is conducted for the purpose of determining qualitatively and quantitatively, within the scope of the method, the quality factors of a weld or a weldment. One may define the term *quality factor* as any factor which contributes to the adequacy of an item with regard to its service performance. Such factors are usually the bases for specification requirements.

Because of the simplicity, low cost and rapidity with which it can be accomplished, visual examination is the most widely used of inspection methods. It should be regarded therefore, as one of the most important methods for determining weldment quality. There are many quality factors which are beyond the scope of visual examination (e.g., metallographic structure, subsurface soundness, etc.). However, careful evaluation of what can be seen on the surface of a weldment or welded joint can contribute much toward the final determination of its acceptability, particularly when this information is used in conjunction with findings by other inspection methods. Visual examination can be subject to all types of welds and weldments. As is the case with all inspection methods, proper application and correct interpretation of results are essential to its usefulness and success. Details of where and how to examine are given in the following paragraphs.

Application

General Aspects.—The equipment required for visual inspection is extremely simple. Adequate lighting is of primary importance and may be obtained by means of a good extension lamp or flashlight if light from general sources is not satisfactory. A hand magnifying glass or other means for obtaining magnifications of low power will be found helpful. In cases where the insides of welded vessels or other hollow shapes are to be examined, a borescope or other optical device for internal inspection may be found necessary. The required scales and gages for checking the accuracy of dimensions and the extent of warpage or distortion should also be available.

In order to obtain the most complete picture of the quality of the product, visual inspection operations should be synchronized with fabricating operations. Most welding processes require a certain amount of material preparation before welding is actually begun. A visual check of the material prior to welding for the purpose of checking the material itself and also its preparation (descaling, scarfing, cutting, etc.) will enable early detection of many causes of poor quality. The examination of welded joints or parts thereof which are inaccessible in the finished product should be accomplished during the progress of work when these joints are available for examination. A good example of this situation is the case of a multilayer arc weld where the root pass, later to be covered by subsequent passes, should be examined while still visible. Because of the importance of this synchronization of examination with welding operations, the details of application of this inspection method given below are divided into three main categories: examination prior to welding, during welding and after welding.

Examination Prior to Welding.—The quality of a welded joint can be attributed to both the welding process and the materials which are joined. Before any welding is performed the inspector should

examine the faces and edges of material for such flaws as laminations, blisters, scabs, seams, etc. Heavy scale is detrimental to all welding and even oxide films, grease, paint, and oil may be of importance when looking for sources of inferior weld quality. Resistance welding, induction welding and brazing are particularly sensitive to the presence of foreign material on the surfaces to be joined. A check should be made of the size and shape of pieces to be welded. Warped, bent or otherwise damaged material if detected at an early stage of fabrication may save much time and labor in attempting to correct these faults at a later stage. When edge preparation, such as scarfing, is required the bevel angle and the presence of residual scale or excessively rough surface due to the cutting operation should be noted. The alignment of parts and the fit-up, including root opening, should be checked for conformance with requirements. Such details are often adjusted by means of holding jigs or fixtures. Flaws such as cracking or porosity may occur due to the chilling effect. Where backings are required for arc or gas welding, their presence, proper position and construction should be checked. When a brazing process is used, the manner in which flux is applied to the joint is of extreme importance and depends upon the type of joint and the brazing process to be employed. The flux application should be continuous, with no bare spots showing. An inspection of the fluxed but unjoined metal will serve as an indication of its cleanliness. If the flux tends to ball-up and provide a discontinuous coating, improper cleaning may be indicated.

Examination During Welding.—Available inspection methods are incapable of determining all of the factors involved in weld quality when applied to the finished product alone. Therefore, certain requirements regarding welding must be imposed to obtain assurance of quality. These requirements may pertain to such factors as joint design, type and polarity of current, electrode pressure, composition of filler metal, etc., depending upon the particular welding process involved. Although some of these factors may seem outside the realm of visual examination (checking welding current is an electrical measurement), they are included here for completeness. When welding procedure factors are controlled by specification or code requirements, a visual check of each factor should be made to determine conformance.

When arc or gas welding is employed and filler metal is to be applied in two or more layers it is desirable to inspect the surface of each layer of weld metal before it is covered by subsequent layers. When the necessary inspection personnel are available for this inspection, conditions such as slag accumulation in arc welds, poor fusion and cracks may be detected and remedied when most accessible. A *workmanship standard* (see Fig. 30) is useful in judging the appearance of weld metal surface produced by these processes. Surface appearance, beyond regard for the esthetic features of a weld, indicates the degree of care in its production and the inspector may infer good or poor weld quality on this basis pending results of more searching tests or examination. Such a workmanship standard may be constructed to indicate the appearance of the surface of first deposited layers as well as the surface of the last layer of a weld. While examining the root pass for possible defects the inspector should recheck the groove faces of the metal to be joined for seams, laminations, etc., which often open up under the welding heat and are only obvious after the first or subsequent weld pass. Particular emphasis should be placed upon the importance of examining the root pass of arc welds. Because of the geometry of the joint, the relatively large volume of base metal with respect to that of the root pass weld metal, the fact that the plate may be cold and the possibility that the arc may not penetrate into the root, the root pass solidifies quickly and in so doing tends to trap slag or gas which is more difficult to remove after making subsequent passes. In addition, the root pass is particularly susceptible to cracking and the cracks which form may extend to the overlaying weld metal as it is deposited. In the case of groove welds, slag covering the surface of the root pass will be trapped by the second pass on either side of the joint if not completely removed. Visual examination is used as a check on such cleaning operations.

With regard to resistance welding, a visual check of the abutting or overlapping of edges for compliance with applicable codes or specifications is in order. Spatter which occurs during the welding opera-

tion may be indicative of excessively high welding current and should be noted. The operation of welding equipment and its condition is of importance from the inspection point of view. For example, in the case of spot-welding equipment, the electrodes should be checked for change in size and contour as welding progresses. Any variation in the size of the electrodes will of course alter the size of the weld itself. If the welding machine is not equipped with an automatic welding current control, the amount of metal in the throat of the machine should be checked. Electrode pressure must be verified occasionally and a check of air supply

unit operations. In furnace brazing, pieces in different parts of the furnace should be checked to ascertain that they are all up to proper brazing temperature. In torch brazing the inspector should note that the force of the brazing torch flame does not blow the flux or brazing alloy away from the joint. The inspector should see that the weldment is not moved or strained in such a way as to cause cracking until the brazing alloy has gained sufficient strength by cooling.

Examination After Welding.—Visual examination is useful for inspecting the finished product of all types of welding for such quality factors as:

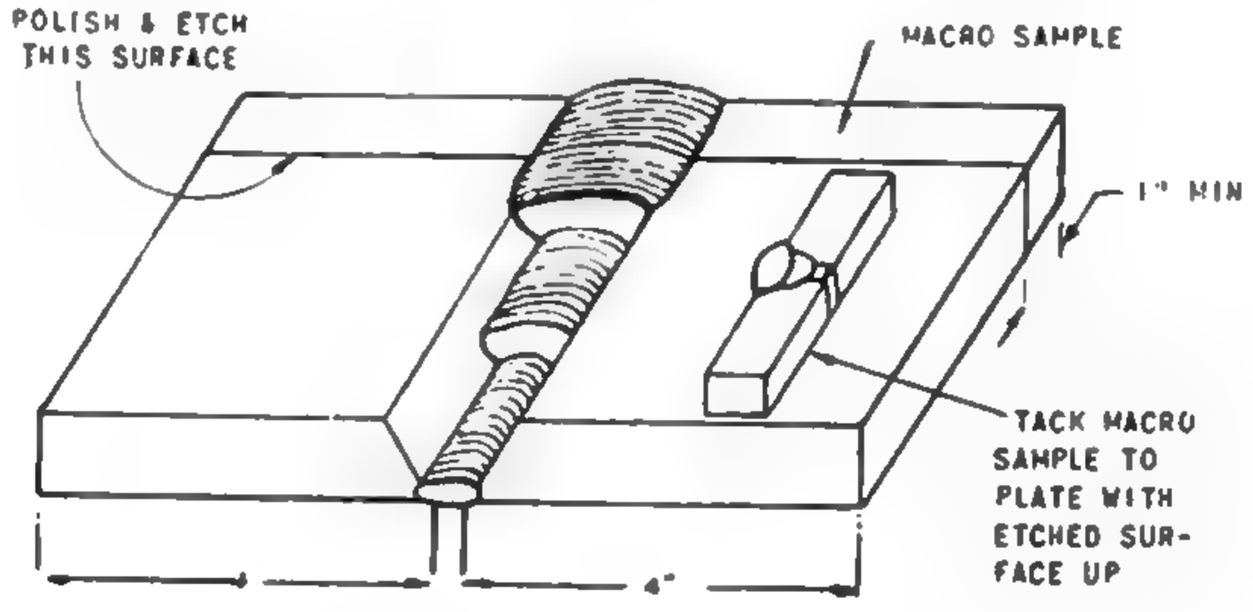


Fig. 30.—Workmanship Standards

Illustrating suitable standards for groove welds (top) and fillet welds (bottom).

lines and gaskets to detect leakage is desirable.

When a brazing process is being used and the parts joined are of unequal thickness, it is important that the lighter gage material is not overheated before the heavier pieces are brought up to brazing temperature. Uniformity of heating in general should be checked. This is true of multi-station brazing as well as single-

1. Dimensional accuracy of the weldment (including warpage).

2. Conformance to specification requirements regarding the extent, distribution, size, contour and continuity of welds.

3. Weld appearance, i.e., regularity, surface roughness, spatter, etc.

4. Flaws such as cracks, porosity, unfilled craters and crater cracks par-

ticularly at the ends of welds, undercutting, etc.

The dimensional accuracy of weldments may be determined by conventional methods and need not be elaborated upon in this section. The conformance to specification requirements of welds made by arc and gas welding and brazing may be checked by means of a weld gage as shown in Fig. 31. This gage is used for fillet welds only. The size of the weld is determined in terms of the length of the leg. The gage may be used to determine whether the size is within allowable limits and whether there is excessive concavity or convexity. The particular gage shown is made for use on joints between surfaces that are perpendicular or nearly so. Special gages may be made for use where the surfaces are at acute or obtuse angles.

satisfactory will greatly facilitate the judgment of appearance of welds. As is the case with all welding, a good weld is not necessarily predicated upon its good appearance, however a good appearing weld is the least that can be required and indicative of a general high quality level of workmanship.

The examination of a weld for flaws which may affect its service performance should be preceded by adequate cleaning of the weld surface to remove slag, oxide or other coatings which are formed during some welding operations. Such cleaning must be carried out carefully so as not to obscure existing faults. Chipping and shot blasting are examples of cleaning methods which, if not carefully conducted, may peen over fine cracks so as to make them invisible.

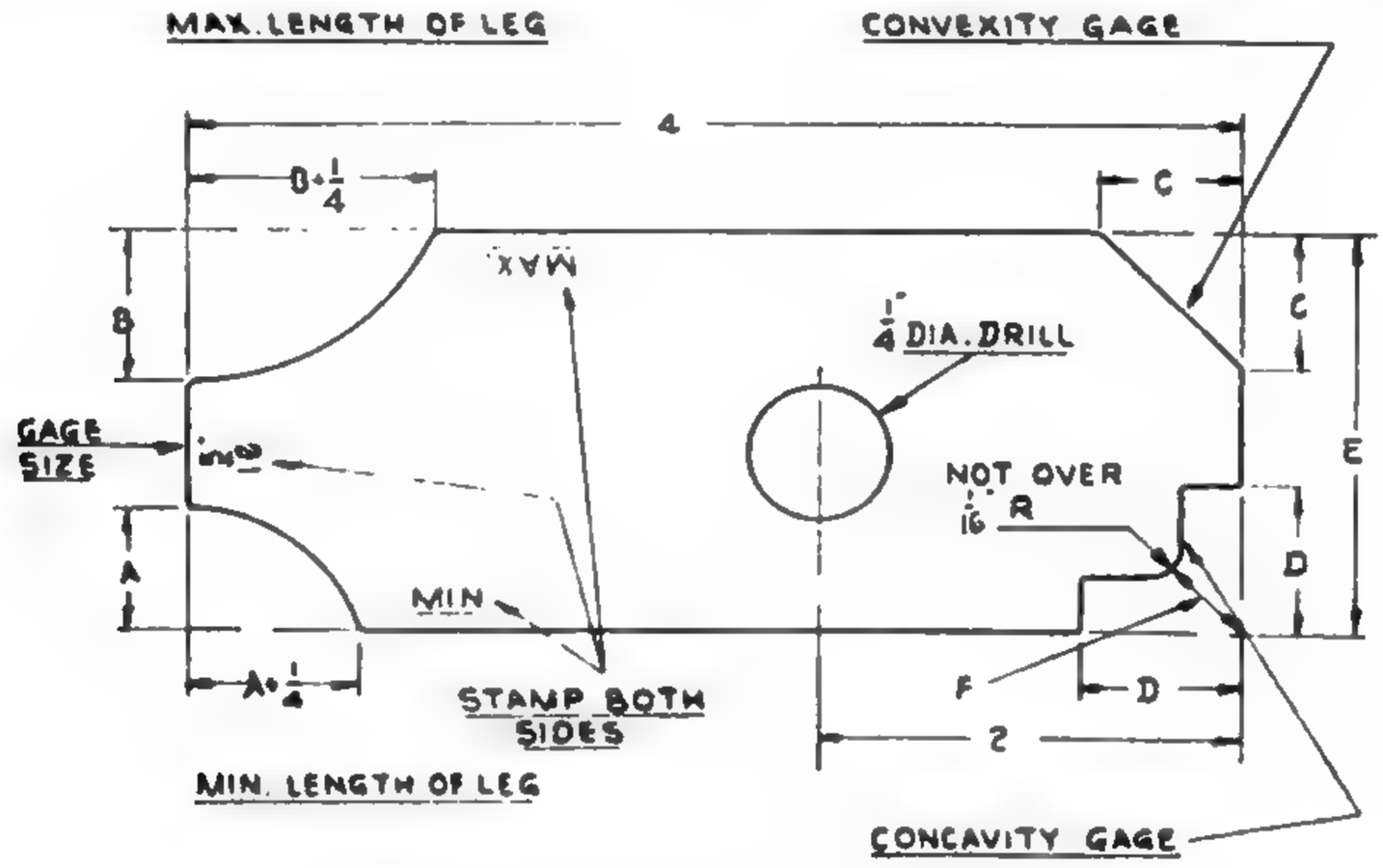


Fig. 31.—Typical Fillet Weld Gage

For welds made in grooves (braze-welding, arc and gas welding) the following should be considered: the width of the finished weld should be in accordance with the required groove angle, root face and root opening. The height of reinforcement should be consistent with specification requirements or accepted good practice. Particularly where welding or brazing is performed from one side of the joint only, the opposite side should be checked for penetration of weld metal or brazing alloy through the joint.

A good induction weld should be smooth and continuous. A notched or saw-toothed effect is due to an excessively long time cycle during welding.

Requirements as to surface appearance differ widely. The use of a sample of welding which has been agreed upon as

A discussion and description of types of flaws which occur in the various types of welds are given in the preceding section of this chapter and need not be repeated here.

Evaluation of Results

Standards, as they are generally considered, are not often available for the use of the inspector in evaluating the acceptability of welds or weldments on the basis of visual inspection. The workmanship standard mentioned previously is of great value in connection with the general appearance of a weld. However, code or specification requirements plus a sound knowledge of the particular welding process and the service requirements for the weldment are usually coupled with good judgment to help the

inspector make his evaluation of the quality of the weld based on visual examination.

CHEMICAL ANALYSIS

Chemical tests ordinarily are performed either for chemical analysis or corrosion resistance. Tests for chemical analysis are required to ascertain whether the base metal and the weld metal meet the analysis requirements of the applicable codes or specifications. Special analyses of base metal and weld metal are used for special service requirements. Experience has shown what range of chemistry is best for a particular service condition. Trouble is often encountered in welding which can be traced by analysis to off-heats of metal. This may be due to a high sulfur or phosphorus content or to harmful residuals entering the metal from the scrap that was used. The overall analysis of the material may be correct, but segregation of harmful elements may be present and give trouble. In these cases careful methods of sampling for analysis must be used. In general, the analysis of the weld metal is specified to be in the same range as that of the base metal. Sometimes, however, a weld metal of greatly different analysis than that of the base metal is specified, depending on service requirements.

Since weldments must operate in all types of corrosive liquids, solids and gases, a large number of corrosion tests have been devised to check the material to see if it will meet required service conditions. The best test is actual use under service conditions, but time limitations and expense usually prohibit its application. Consequently, a large number of laboratory-type tests have been evolved which give partial but satisfactory information. A few of the corrosive conditions to which weldments are subjected are under-soil attack of various types, salt water and salt spray, attack due to various atmospheres and waters, electrolytic and chemical action of all sorts and high temperature conditions of various kinds.

Corrosion tests are required in but few codes and specifications as most metals are chosen for specific use by previous experience. The chemical industry, which is constantly handling new products, has evolved numerous corrosion tests which are usually required to be applied to the base metal and welded joints of weldments. Perhaps the best known test is the salt spray test. (Reference may be made to *ASTM Standards, Part I, Metals,* for a complete description of this test.)

Welds are made in a multiplicity of metals such as iron, nickel, copper, aluminum, magnesium and their alloys. All the above metals are used under specific corrosion conditions, and consequently a complete discussion of the various corrosion tests involved is beyond the scope of this chapter.

METALLOGRAPHIC TESTS

Metallographic tests are not often required in welding specifications. They are carried out for various purposes such as:

(*a*) To determine the distribution of nonmetallic inclusions.
(*b*) To determine the number of weld passes.
(*c*) To determine the grain structure in the weld and fusion zone.
(*d*) To determine the extent and structure of the heat-affected zone.

They may involve merely visual examination in which case the specimens, called macro specimens, are etched to bring out the structure and examined by the unaided eye or at low magnifications; or they may involve microscopic examination, in which case the specimens, called micro specimens, are prepared and etched for examination under the microscope at high magnifications. A complete description of the preparation of test specimens and of accepted etching reagents will be found in the ASM *Metals Handbook.*

Sample and Sample Preparation.— Samples may be secured by sectioning the weld or by means of a core drill or by trepanning. In the two latter cases the drilled hole or the trepanned cut may be rewelded and the weldment thus rendered fit for service. Such tests may be regarded as essentially non-destructive.

Samples secured by any of the above methods are prepared by cutting to reveal a desired surface which is further prepared for examination.

For macroscopic examination of iron and steel, the surface to be examined may be prepared by one of the following methods:

(*a*) Without requiring any finishing or other preparation, place in boiling 50% solution of hydrochloric (muriatic) acid until there is a clear definition of the structure of the weld. This will require approximately one-half hour.

(*b*) Grind and polish specimens with emery wheel or emery paper and then etch by treating with a solution of one part ammonium persulfate (solid) and nine parts of water by weight. The solution should be used at room temperature and should be applied by vigorously rubbing the surface to be etched with a piece of cotton kept saturated with the solution. The etching process should be continued until there is a clear definition of the structure of the weld.

(*c*) Grind and polish specimens with emery wheel or emery paper and then etch by treating with a solution of one part of powdered iodine (solid form), two parts of powdered potassium iodide and three parts of water, all by weight. The solutions should be used at room temperature and should be brushed on the surface to be etched until there is a clear definition of the structure of the weld.

After being etched, the speciments are washed in clear water and the excess water removed. They are then immersed in ethyl alcohol and dried. The etched surfaces may then be preserved by coating with a thin, clear lacquer. Some typical macro samples will be found in various chapters in this HANDBOOK.

The specifications under which the weldment is constructed will define the types, sizes and number of defects allowable for the particular type of welded joint. Where a defect is located, additional specimens are usually cut at certain intervals on each side of the defective segment wherever the joint length will permit. If additional defects are found, more specimens are usually cut until the limit of the defective welding has been definitely established.

In the examination for exceedingly small defects or for grain structure at high magnification, specimens may be cut from the actual weldment, as above, or from welded test samples. The samples are prepared with a highly polished mirror-like surface and etched for examination under high-powered microscopes to show the structure of the base metal, heat-affected zone, fusion zone and weld metal. These specimens are called micro specimens and are most often specified for alloy steels or nonferrous metals. Typical photomicrographs will be found in various chapters in this HANDBOOK. For a detailed discussion of microscopic examination procedures, reference may be made to *ASTM Standards, Part I, Metals.*

MAGNETIC PARTICLE INSPECTION

General

Magnetic particle inspection is a nondestructive method for detecting cracks and other discontinuities, at or near the surface in magnetic materials. It should be kept in mind that magnetic particle inspection produces indications of discontinuities which may or may not be defects. It is necessary for the inspector to properly interpret these indications to determine what types of discontinuities are being indicated. It is then necessary to determine whether or not these discontinuities will affect the performance of the weldment in service. Since wide variation is possible in the inspection technique and in the evaluation of the results, it is absolutely essential that the following points be discussed and agreed upon:

1. What weldments or sections of weldments are to be inspected.
2. What techniques to use (these should be specified in exact detail).
3. What types of discontinuities should be rejected.
4. What type of discontinuities may be accepted.
5. Definition of reworking and subsequent retesting which may be permissible.

Since this method depends upon producing, recognizing and evaluating visual indications, its success or failure depends primarily upon the care and knowledge of the personnel actually performing the inspection. Because of this, it is essential that the inspectors be selected and trained for this type of work. This includes not only knowledge of how to produce indications but how to carefully interpret them and how to apply standards of evaluation which have previously been discussed and decided upon.

Basic Principles.—Magnetic particle inspection depends on simple magnetic and electrical principles. By the use of high amperage electrical currents, a strong magnetic field in the proper direction is set up in the piece being inspected. A leakage field will be set up by a discontinuity

which intercepts the field in the part (Figs. 32 and 33). This leakage field produces local poles which will attract and hold finely divided magnetic particles. The pattern thus produced on the surface of the part indicates the presence of a discontinuity or defect.

Scope of Application.—The method can be used to inspect welds or other parts made of magnetic materials, such as iron and the magnetic alloy steels. It may also be used to inspect plate edges prior to welding and for inspection of parts being repaired by welding.

Defects which may be detected in welds by magnetic particle inspection include surface cracks of all kinds, both in the weld metal itself and in the adjacent base metal; laminations or other defects on the prepared edge of base metal; incomplete fusion and undercut; subsurface cracks; and inadequate penetration at the root. Although subsurface defects may be detected by magnetic particle inspection under suitable conditions, it is most reliable for the detection of surface defects.

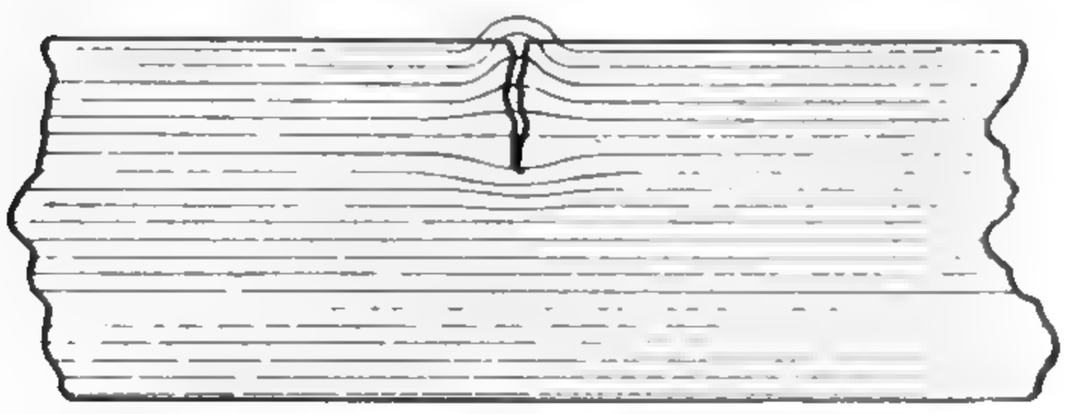


Fig. 32.—Magnetic Flux Distribution and Leakage Field in Magnetized Part with Surface Discontinuity

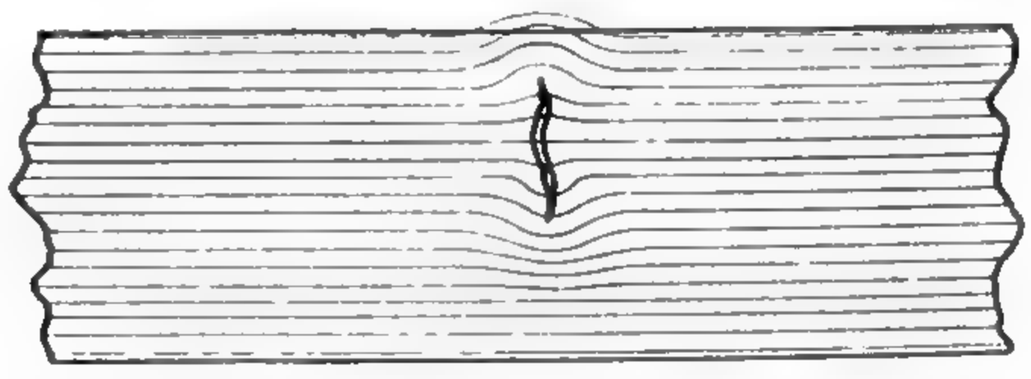


Fig. 33.—Magnetic Flux Distribution and Leakage Field in Magnetized Part with Subsurface Discontinuity

Limitations.— Being a magnetic method it is applicable only to ferromagnetic materials in which the deposited weld metal is also ferromagnetic. It cannot be used to inspect nonferrous materials or the austenitic steels. It may also be difficult or impossible to inspect a weld between metals of widely dissimilar magnetic characteristics or welds where the magnetic characteristics of the deposited metal are appreciably different from the base metal. Joints between metals of dissimilar magnetic characteristics create magnetic discontinuities which may produce indications even though the joints themselves may be sound.

The sensitivity of this method in the detection of subsurface defects decreases with a decrease in the size of the discontinuity and also decreases with increased depth below the surface. The method is more sensitive to long crack-like discontinuities than to those that are rounded or more nearly spherical in shape. The method affords maximum sensitivity on defects which are essentially normal to the surface on which the inspection is being carried out. For example, laminations cannot be detected by this method from the top or bottom surface of a plate but can be detected if the plate is inspected along the edges where the laminations are essentially at right angles to the surface being inspected. A discontinuity is also best indicated if it is essentially at right angles to the magnetic flux in the part. This condition is brought about by using those techniques which will set up a magnetic field in the proper direction or directions.

The sensitivity of the method is affected by the surface conditions existing at the time inspection is carried out. Normally, however, no special surface preparation such as machining or grinding is necessary. The surface must be clean and dry; oil, water, excessive slag or rust accumulations will interfere with proper inspection. Wire brushing, sand blasting or comparable surface cleaning is usually satisfactory and most welds may be inspected without further preparation. Surface roughness, however, does decrease the sensitivity of the method in detecting subsurface discontinuities. Unusual roughness distorts the magnetic field and also interferes mechanically with the formation of the powder patterns. If the surface is unusually rough, it may be advantageous to lightly grind it before inspection. If questionable patterns appear on rough welds, it is advisable to grind the surface slightly and then reinspect.

Interpretation of Indications.—Indications of surface cracks, in general, consist of powder patterns which are sharply defined, tightly held and usually quite heavily built up with powder. Indications of subsurface discontinuities on the other hand,

are usually less sharp, of fuzzy appearance and less tightly adherent. After some experience an inspector can form an opinion as to the severity of the defect or its distance below the surface by the nature of the pattern. Typical crack patterns are illustrated in Fig. 34. Crater cracks are recognized by their patterns, which are usually small and occur at the terminal point of the weld. They may be a single line in almost any direction, multiple or star shaped. Incomplete fusion will produce an accumulation of powder which

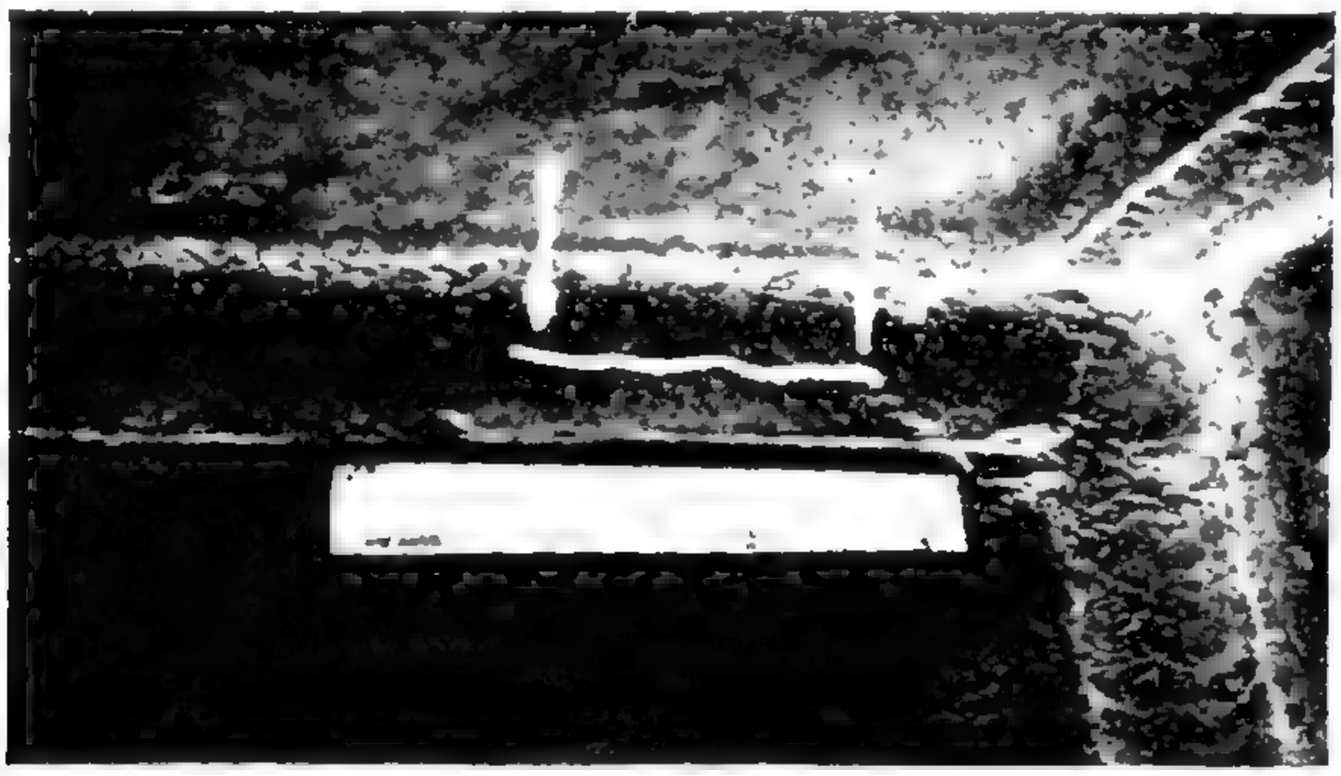


Fig. 34.—Surface Cracks

Illustrating the pattern of a center-line (longitudinal) weld crack (upper) and a crack (longitudinal) in or near junction of weld with base metal (lower).

will generally be fairly pronounced; visual appearance of the weld edge will usually confirm its presence. The pattern produced by incomplete fusion occurring at the surface is sharper and more tightly adherent than if the incomplete fusion is more deep seated. This type of defect is illustrated in Fig. 35.

Undercut also produces a pattern at the weld edge which adheres less strongly than the indications obtained by incomplete fusion. Undercut also can be detected by visual examination.

Inadequate penetration at the root of a weld or a gap between the plates at the root may produce a powder pattern resembling that produced by a subsurface crack. Such inadequate penetration or gap may not constitute a defect or be objectionable, depending on the requirements of the particular weld. Figure 36 shows a typical pattern obtained when this condition is present.

Subsurface porosity or slag inclusions may produce powder patterns, which are usually not strong nor pronounced and are readily distinguished from indications of surface conditions. Figure 37 illustrates a subsurface defect pattern.

Irrelevant Indications.—Certain conditions in a weld may lead to the formation of powder patterns which are not indications of cracks or other discontinuities and which are of no significance in evaluating the soundness of the weld. These patterns

Fig. 35.—Incomplete Fusion

Pattern at *A* indicates a surface condition. Broadening of pattern at *B* indicates that the condition is more deep-seated.

may be produced by the physical contour of the part or by magnetic discontinuities not affecting the serviceability of the weldment. Such indications may be caused by a thin area of change in section of the part and may occur above or adjacent to an oil hole, a keyway or a lightening hole. These patterns are usually readily identified by their location and the shape of the part. Irrelevant indications may also be produced by an abrupt change in the magnetic characteristics of the material. An example of this is an indication which may occur at the edge of the heat-affected zone

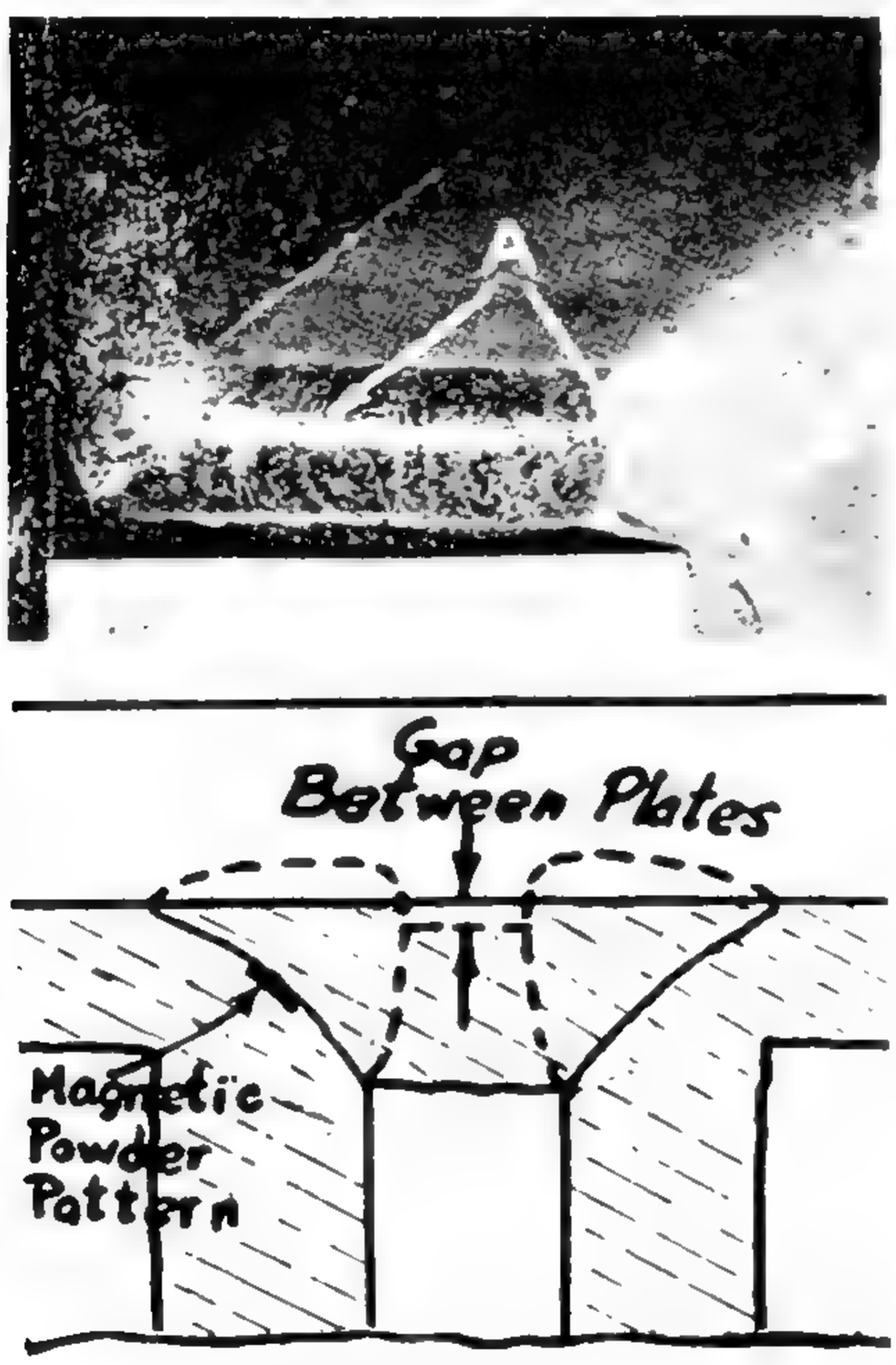


Fig. 36.—Root Gap

Illustrating the pattern obtained (top) when a root gap as shown (bottom) is present.

Fig. 37.—Subsurface Crack

in the base metal of a weld in a high-alloy or air-hardening material. This is in the form of a diffused or fuzzy pattern running along the base metal in a line paralleling and quite close to the edge of the weld. This pattern very closely resembles that caused by undercutting or incomplete fusion. It is, however, very loosely adherent and after some experience can be readily recognized. The indication is caused by change in the magnetic properties of the metal at the edge of the heat-affected zone, and will disappear if the piece is heat treated or stress relieved. A similar pattern may be produced when a ferritic (magnetic) base metal is welded with austenitic (non-magnetic) filler metal. For this reason magnetic particle inspection is not normally recommended for the inspection of welds of this type.

Where unusual patterns are produced for the first time it may be necessary to establish identity by correlating the results with other test methods, such as observation under magnification, sectioning, etching, metallurgical examination, etc. Once the proper interpretation has been established for a given type of indication, this interpretation can readily be applied to similar indications on other similar parts.

Evaluation of Observations.—After a discontinuity has been identified a decision must be made as to whether the weld is acceptable, may be repaired or is to be rejected. In most cases this decision will be governed by applicable specifications, standards or purchase orders. If this is not the case, the discontinuity should be judged on the basis of whether or not it will affect the serviceability of the part in question. Consideration must be given to the shape, size and direction of the discontinuity, as well as its location with reference to the amount and direction of stress in the area in which it is found. It should also be determined whether or not subsequent processing or machining operations would remove the defective area. In general all crack-like discontinuities, particularly those occurring at the surface, are stress raisers from which fatigue or other service cracks may develop or they may be focal points for corrosion.

Techniques

Various techniques and procedures are used, each with certain advantages and limitations. Specific techniques must be determined and defined in detail in order to produce consistent and comparable results.

Type of Magnetizing Current.—Both a.c. and d.c. are used for the purpose of magnetizing the parts to be inspected. These currents are usually high-amperage, low voltage.

Since a.c. has a skin effect it magnetizes only the surface layer of the part. For this reason it is effective only for locating discontinuities extending to the surface. It is suitable for detection of fatigue or service cracks, which normally start at the surface. It is sometimes used to inspect welds in joints designed for incomplete penetration so that surface cracks will be indicated but the unfused root will not.

Some form of d.c. is used for most welding inspection in order to produce a field which will penetrate throughout the part and thus make possible the location of subsurface discontinuities as well as all surface cracks. For purposes of magnetic particle inspection, rectified a.c. gives the same results as d.c. and is considered comparable to straight direct current. Surge characteristics available in rectified a.c. equipment especially designed for this type of inspection and in some motor-generator sets are advantageous in that they enable defects to be located at a greater depth below the surface than with equipment which does not have surge characteristics. If it is desirable to locate subsurface defects the best magnetizing procedure is to use single-phase, half-wave, rectified current. This current combines the advantage of surge characteristics due to the wave form with additional particle mobility due to the pulsating current. Figures 38 and 39 show comparison curves based on threshold indications in an unhardened 0.90% C. tool steel ring, 5 in. O.D., $1^1/_4$ in. I.D. and $^7/_8$ in. long.

Inspection Medium.—Inspection material is available in various forms and colors. The selection depends on the type of surface being inspected and the type of defect to be located.

Dry Method: The materials normally used for the dry method consist of finely divided, ferromagnetic particles in powder form. The particles are coated to afford greater particle mobility. They are also colored to afford maximum contrast with the part being inspected and are available in gray, black and red. The dry method

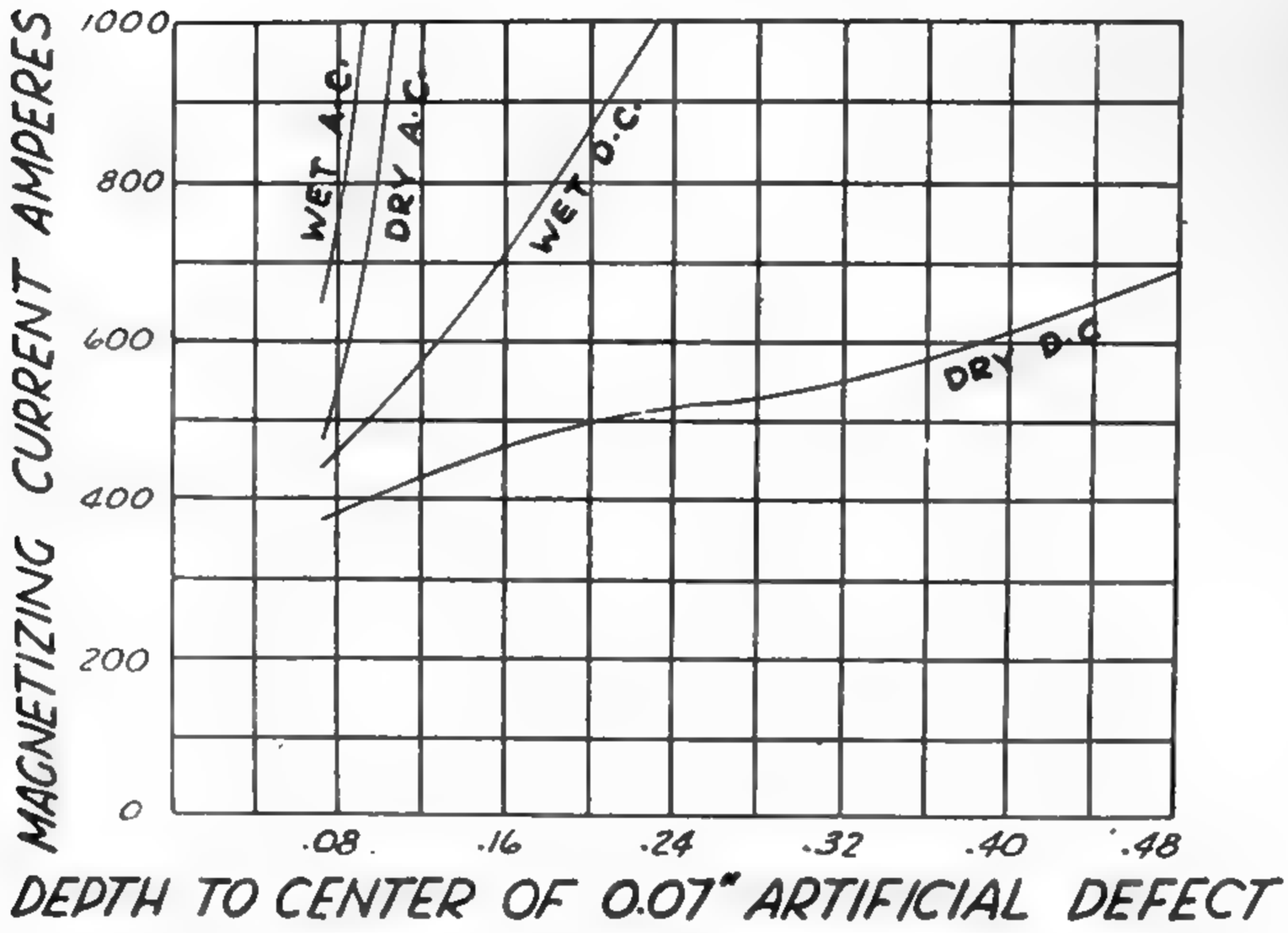


Fig. 38.—Comparison of Wet and Dry Methods Using Both A.C. and D.C.

is easier to use on rough surfaces and is more readily portable. Dry particles also afford greater sensitivity for location of the larger subsurface discontinuities. The powder is usually applied with some sort of hand applicator or by a special powder gun. Care must be taken to apply the powder in the form of a low velocity cloud so that the particles will have an opportunity to line up in indicating patterns as they approach the surface of the magnetized part. Excess powder may be removed from the surface by the use of a low velocity air stream, which should be of sufficient force to just remove the excess powder without disturbing lightly held powder patterns.

Wet Method: The indicating particles used in the wet method are smaller than those used in the dry method. The material is usually furnished in the form of a paste which is mixed with a light oil, such as a highly refined kerosene, in the ratio of approximately $1^1/_2$ oz. of paste to 1 gal. of suspension. The bath must be properly agitated in order to prevent the indicating material from settling out. The inspection medium is applied either by flowing or spraying the suspension over the surface or by immersing the part in

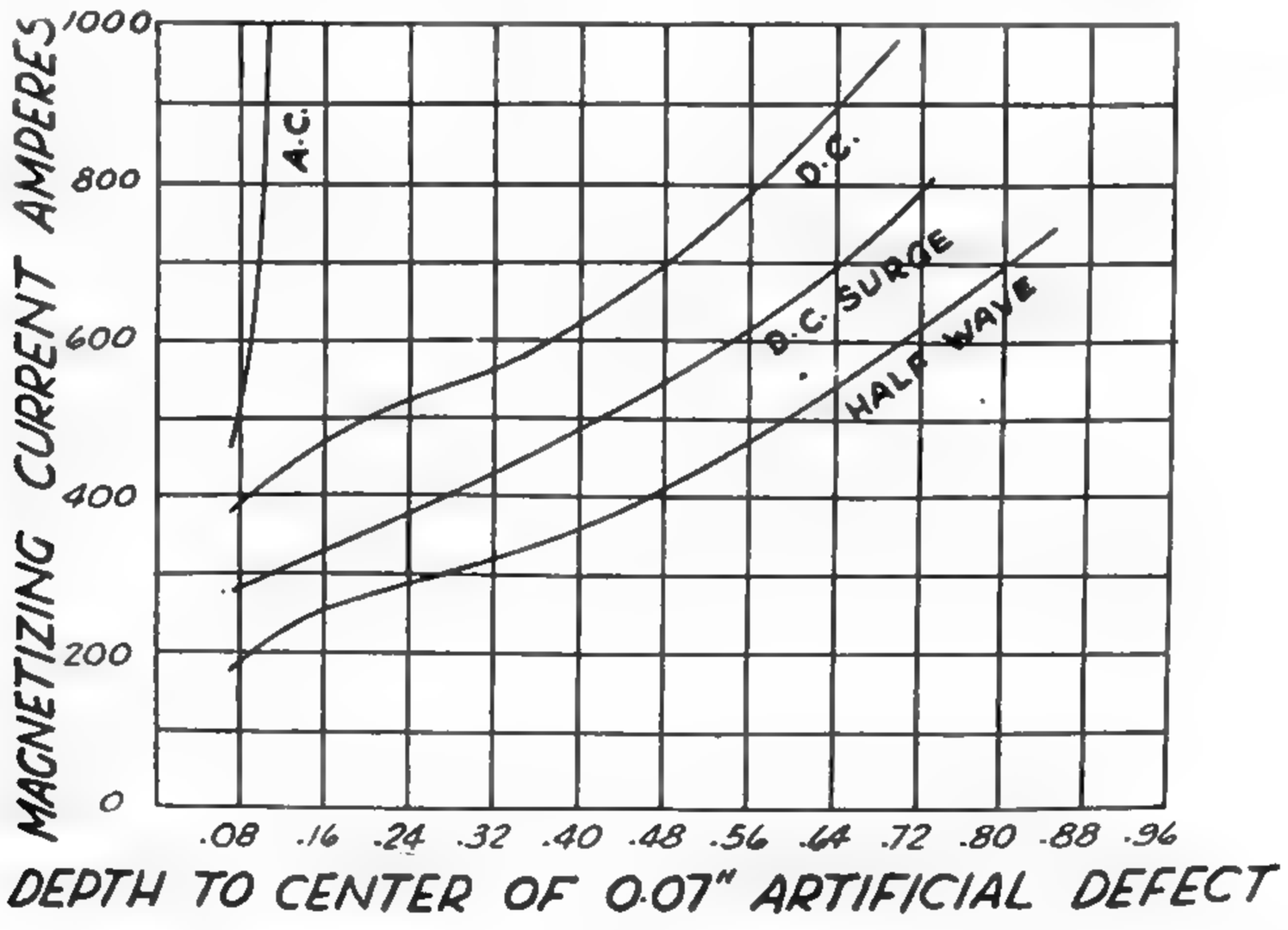


Fig. 39.—Comparison of Sensitivity of A.C., D.C., D.C. with Surge and Half-Wave

the suspension. The wet method is normally used on smaller parts and those having smoother or machined surfaces. It is somewhat more sensitive for indicating extremely fine defects due to the smaller particle size. The materials are available in either red or black and the color affording the best contrast on the parts being inspected is used. Wet method indicating material is also available with the particles coated with a dye which fluoresces brilliantly under ultra-violet (black) light. The bath is mixed in the same way as with the red or black material except that only approximately 0.1 to 0.2 oz. of paste is used per gallon of suspension. The indications must be observed under black light in a dark or shaded area. Because the indications are fluorescent and therefore more readily seen, the fluorescent inspection material increases the sensitivity of the method in indicating very small or fine discontinuities and also assists in more rapidly inspecting irregular or dark surfaces (Fig. 40). The fluorescent magnetic particle method is applicable only to magnetic materials and should not be confused with fluorescent penetrant inspection, as discussed in more detail in the next section of this chapter.

Sequence of Operation.—All magnetic steels will retain some magnetic field after the magnetizing force has been removed. This retentivity varies with different types of material. In general, the hard materials and the higher alloys retain a higher residual field. In some cases this residual field is of sufficient strength to be used for the purpose of magnetic particle inspection.

Continuous Method: With this procedure the indicating medium is on the part while the magnetizing current is flowing. Since the magnetic field in the part is at a maximum while the magnetizing force is being applied, the continuous method offers maximum sensitivity. Most welds are inspected by the continuous method in order to obtain maximum sensitivity for indication of subsurface discontinuities. When inspecting by the dry-continuous method, the magnetizing current continues to flow during the entire time the particles are being applied and the excess particles removed. It should be noted that if the magnetizing current is turned off before removing the excess particles, only the indications held by the residual field will remain. When inspecting by the wet-continuous method, the usual procedure is to flow the indicating suspension over the area being inspected and immediately apply the magnetizing current for a period of approximately one-half a second. This permits the indications to form as the suspension containing the indicating medium flows across the surfaces being inspected. The inspection medium should not be re-applied after the current has ceased to flow as this may wash away lightly-held indications.

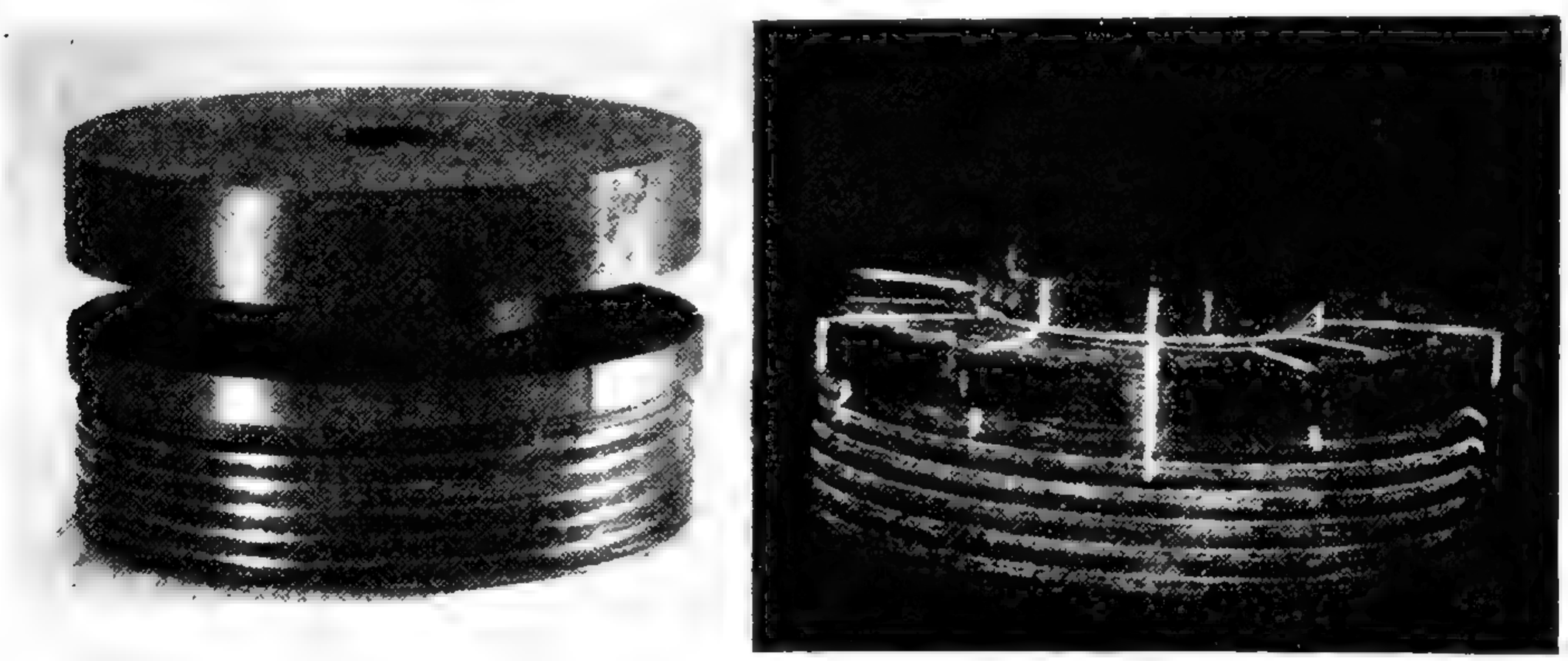


Fig. 40.—Surface Cracks in Irregular Parts

Left—As indicated with black particles. Right—As indicated with fluorescent particles.

Residual Method: With this technique the indicating particles are applied to the part after the magnetizing current has ceased to flow. The residual magnetic

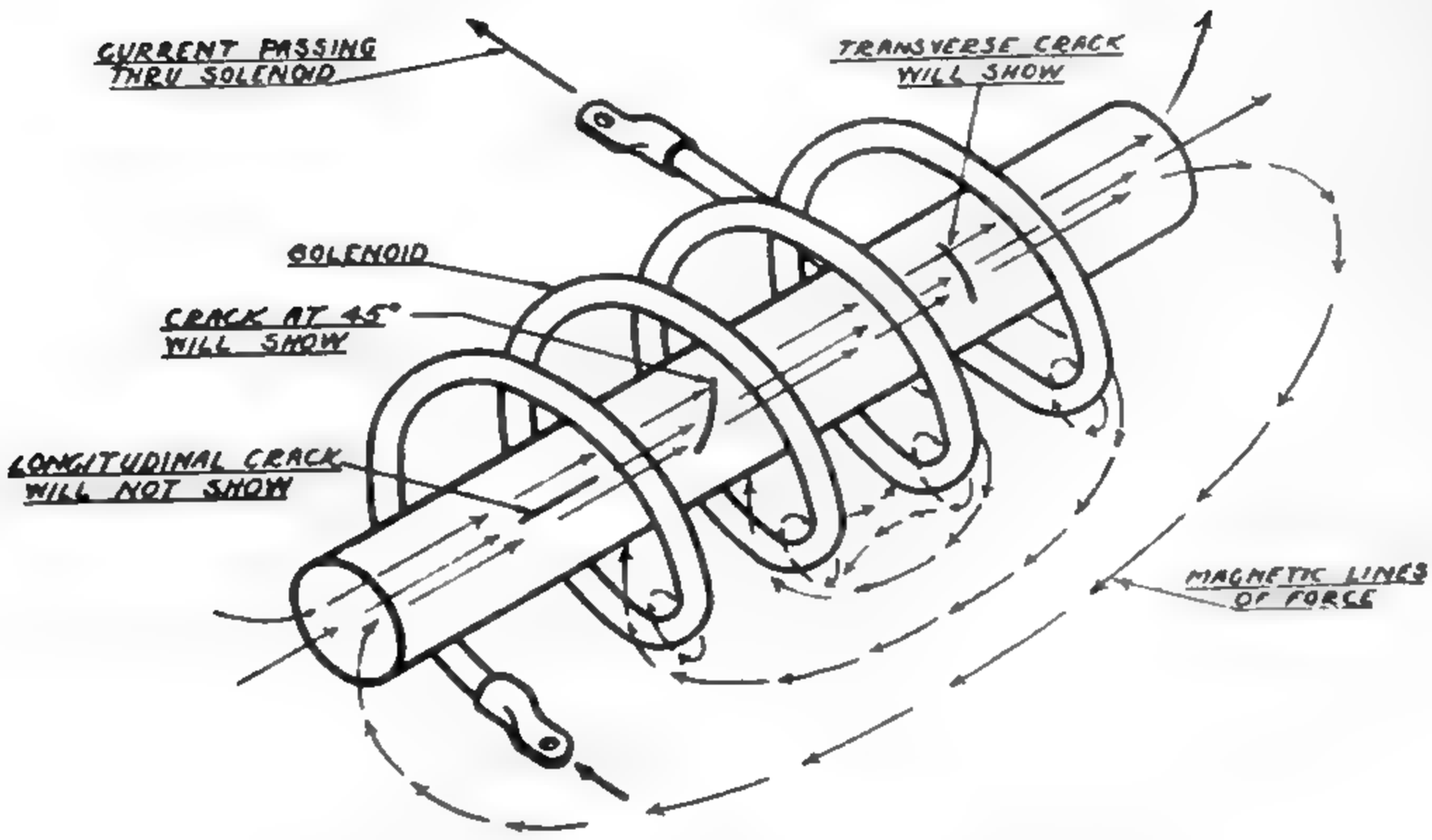


Fig. 41.—Sketch of Longitudinal Field

field remaining in the part is depended upon to attract and hold the indicating patterns. This technique can only be used on materials of relatively high magnetic retentivity. It is usually necessary to determine by actual experiment whether or not the particular material has sufficient retentivity to permit inspection by the residual method.

Orientation of Magnetic Field.—It is necessary to have the magnetic field in a favorable direction in order to produce indications. If the magnetic field is parallel to a discontinuity, the indication may be weak or lacking. Best indications are produced when the magnetic field is essentially at right angles to the discontinuity. Indications will, however, be produced even though the angle between the discontinuity and the field is small as long as the field is not parallel to the discontinuity. Since a magnetic field is always at right angles to the flow of current, best indications are produced when the current is flowing through the part or through the magnetizing conductor or coil in a direction approximately parallel to the discontinuity.

Longitudinal Field: A longitudinal field (Fig. 41) is a magnetic field which extends within the part from one or more magnetic poles to another or other magnetic poles and which has its return path through the air external to the part. It is usually produced by a coil, solenoid or cable wrapping and best indicates discontinuities essentially at right angles to the axis of the coil.

Circular Field: A circular field (Fig. 42) is a magnetic field in a part such that the magnetic flux lines complete their path essentially within the contours of the part itself. With true circular magnetization there are no magnetic poles and little external leakage field. Circular magnetization best indicates discontinuities essentially parallel to the direction of current flow.

The part may be circularly magnetized overall by using the part itself as a conductor (direct method) or by threading a conductor through a central opening in the path (indirect method). It is advantageous to use a central conductor to obtain circular magnetization whenever possible because a more uniform field is produced throughout the part and because it eliminates the problem of making suitable contacts to carry the high amperage current through the part itself.

On large parts or where it is desired to inspect certain specific areas, it may be impossible or impractical to magnetize the piece as a whole. In this case the part may be magnetized locally by passing current through areas or sections of the part itself by means of contacts or prods. This produces a circular field in the area be-

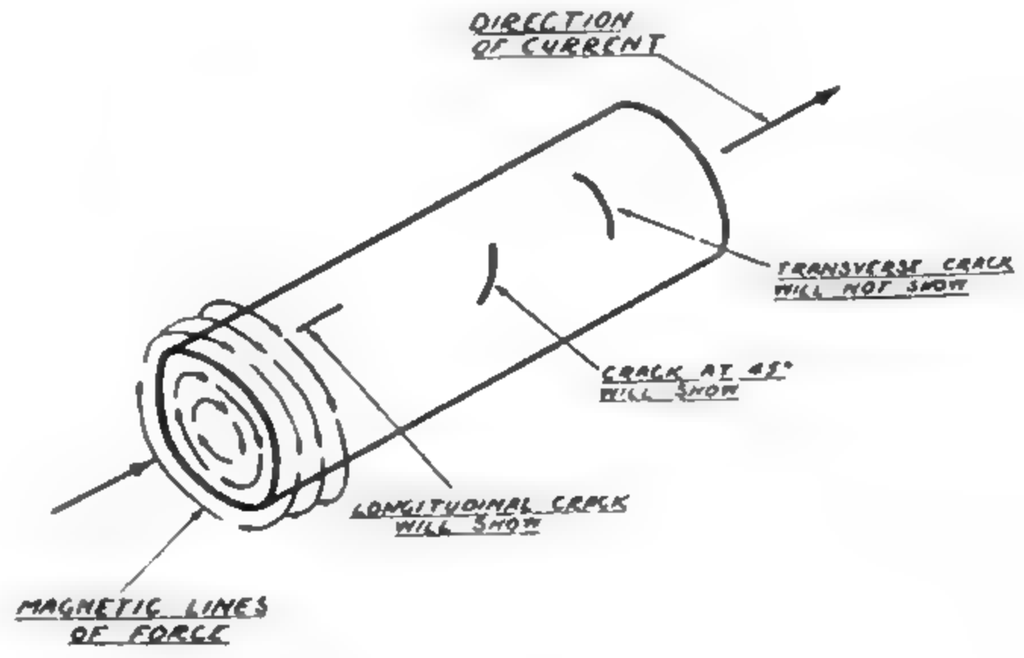


Fig. 42.—Sketch of Circular Field

tween the contact points. This technique is usually used in the inspection of heavy weldments where the weld and adjacent metal only are to be inspected. Care must be taken that the contact prods and the areas being inspected are sufficiently clean to permit passage of the high amperage current without arcing or burning. In the case of high-alloy materials which are air-hardening, hard spots or even cracks may be produced by such local overheating which might affect the serviceability of the part. It is usually advisable to use equipment with a low open-circuit voltage (2 to 16 volts) for this purpose in order to prevent burning and also to prevent arc flash which might be injurious to the inspector's eyes.

Amount of Magnetizing Current.—It is necessary to have sufficient field strength to properly indicate all discontinuities which might affect the performance of the weldment in service. Excessive magnetizing currents, however, are disadvantageous because they may produce irrelevant patterns due to surface field or due to the irregular contours of the part. In many cases the magnetizing current requirements should be determined by specifications, standards or purchase orders. Where such specific instructions are not available, current requirements may be determined by experience or by actual experiments. Usually, however, a considerable latitude in the magnetizing currents is possible without appreciable variation in the indications obtained. The voltage used has no effect on the magnetic fields produced and it is therefore advantageous to use as low a voltage as possible in order to minimize contact problems and also to prevent overheating the parts and equipment. The following figures indicate approximate amperage ranges which may serve as a guide to assist in setting up procedures for this type of inspection:

Longitudinal Magnetization:

Dry method—100 to 400 amp.-turns per in. of coil diameter.

Wet method—400 to 1000 amp.-turns per in. of coil diameter.

Overall Circular Magnetization:

Dry method—100 to 400 amp. per in. of outside diameter of part.

Wet method—500 to 1200 amp. per in. of outside diameter of part.

Local Circular Magnetization:

Dry method—300 to 1200 amp. with contact spacings of from 4 to 12 in.

Wet method—500 to 1500 amp. with contact spacings of from 2 to 12 in.

Demagnetization.—Most weldments do not require demagnetization after magnetic particle inspection. Mild steel does not retain an appreciable residual field after the magnetizing force has been removed. A residual magnetic field in a part has no appreciable effect on its mechanical characteristics so that demagnetization is not necessary unless the part retains a strong residual field which interferes with subsequent machining or arc-welding operations or is to be used in structures such as aircraft, where the magnetic field might affect sensitive electrical instruments. If demagnetization is necessary, the usual procedure is to draw the part through a high field intensity, a.c. coil. The coil preferably should be kept as small as possible. Larger parts may be demagnetized by subjecting them to an a.c. field which is gradually reduced in intensity to a negligible amount. On parts difficult to demagnetize, hammering them and/or rotating them in the field will sometimes be of assistance. Long structures should be demagnetized with their axes in an east-west direction to minimize the effect of the earth's field. Heat treating or stress relief will also demagnetize weldments.

Equipment Used

The basic equipment for magnetic particle inspection is relatively simple. It includes convenient facilities for setting up suitable fields of proper strengths and in correct directions. Means are provided for adjusting the amount of current flowing, and an ammeter, plainly visible to the inspector, should be provided in the magnetizing circuit so that the inspector will know that the correct magnetizing force has been applied for each inspection. Facilities are needed for correct application of the indicating medium. In some cases it may also be necessary to provide facilities for demagnetization after inspection. Special semi-automatic or automatic equipment may be used for more rapid and economical inspection of parts on a production basis.

Stationary Equipment (Wet Method).—For inspection of smaller parts, where it is more convenient to bring the part to the unit, stationary equipment (Fig. 43) is used. General purpose equipment usually provides clamping heads for circular magnetization and a coil for longitudinal magnetization. This type of equipment

usually has a maximum available magnetizing current of from 3000 to 5000 amperes. High amperage, direct current may be obtained from heavy-duty rectifiers or batteries; high amperage, alternating current is obtained by use of transformers. Means are provided for adjusting the amount of magnetizing current and also for applying the current impulse at the correct time and for the correct duration. A V-type tank is used for the inspection medium which should be agitated by air or pump so that a constant concentration of the magnetic particles will be maintained throughout this suspension. Units having an a.c. output may also be used for demagnetization after inspection. Separate, high-field strength, a.c. coils are used for demagnetization in conjunction with d.c. equipment. By the use of external cables, and suitable clamps or prods, large pieces may be inspected external to stationary units. This may be done using either the wet or dry method.

Portable Equipment (Dry Method).—For the inspection of large parts, portable equipment (Fig. 44) is more convenient so that it can be positioned adjacent to the piece being inspected. This type of equipment normally has a maximum output of up to 3000 amp. and is equipped with suitable switches for convenient control of the amount and application of current. High amperage, d.c. may be obtained from rectifiers, batteries or motor-generator sets. High amperage, a.c. is obtained through suitable transformers. The magnetizing is done by use of portable prods, contacts or coils connected to the unit by flexible cables. A remote control switch should be provided which may be built into the prod handles. Special gun-type applicators are available for more rapid and uniform application of dry powder. These deliver either low velocity clouds of powder or light streams of air to blow off excess indicating material. Each is also equipped with a light which materially assists in inspection of large, irregular weldments. This equipment permits inspection of welds in any position. Powder may also be applied with a small rubber spray bulb or a shaker. Care should be taken to dust on the powder very lightly and sparingly.

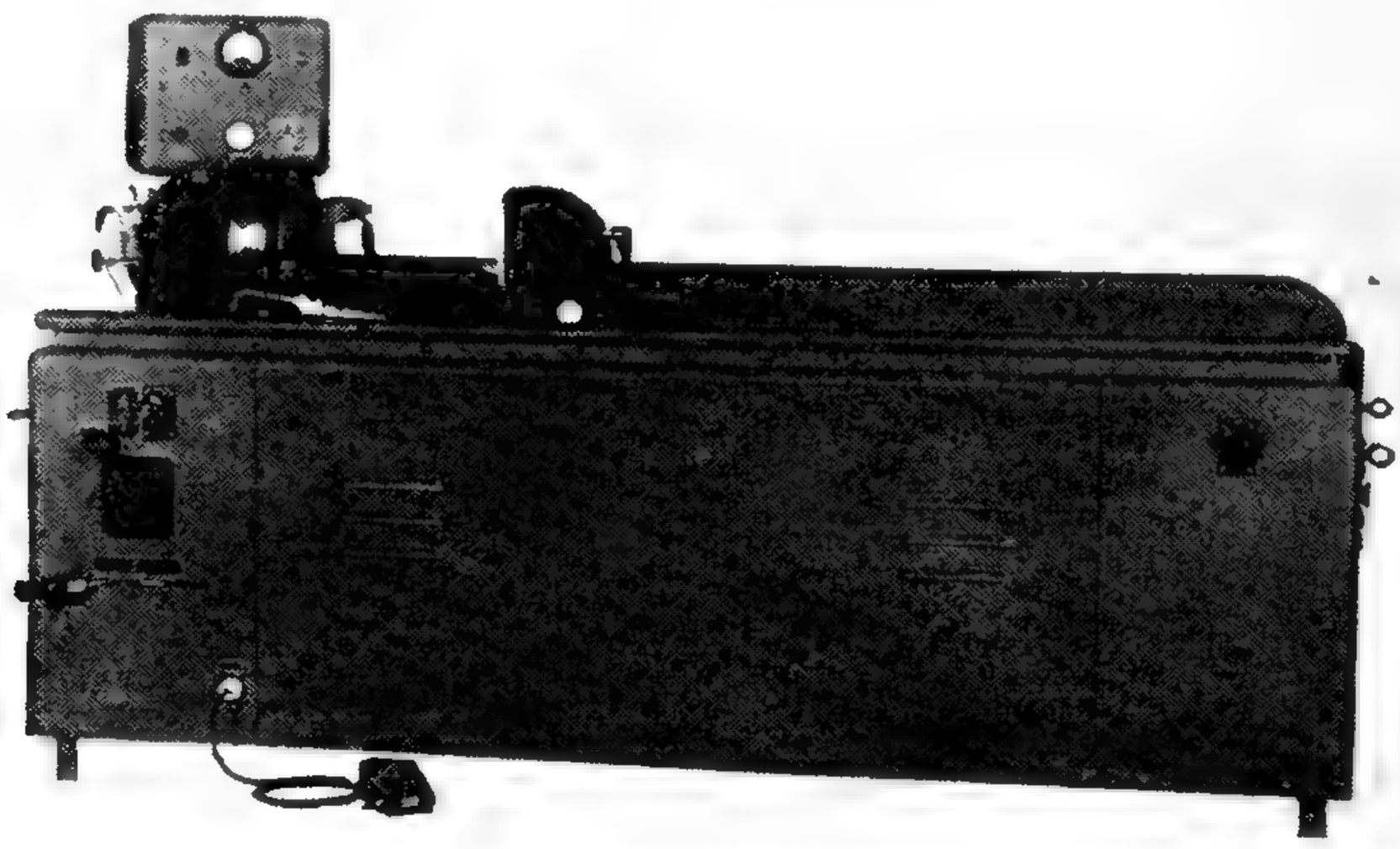


Fig. 43.—Typical Stationary Equipment

Suitable for inspection of small weldments by wet method.

When a hand applicator is used, a low-velocity air stream from a hand bulb or a small air hose may be used to remove excess powder.

Recording Indications.—It is often desirable to make a permanent record of indications obtained. This is quite simply accomplished by the use of transparent cellulose (Scotch tape) transfers. A piece of tape slightly longer than the indication is placed on the indication, tacky side down, and pressed firmly onto the part. The tape may be either left on the piece or upon removal will bring the powder pattern with it. It may then be mounted on a piece of white paper or directly on the inspection report as a

permanent record. When inspecting with dry powder best results are obtained by blowing excess powder from around the indication and by having a surface reasonably free of oil, moisture and dirt. When used with the wet method the oil must then be removed from and around the indication to prevent smearing and distortion when tape is applied. This is most easily accomplished by permitting the part to dry in the air for four to five hours and drying the part with warm air or careful application of a volatile solvent.

It is frequently desirable to record not only the appearance of the indications on a part, but also their locations on the part. In this case the tape should be cut long enough not only to cover the indication, but also to extend to a corner, hole, keyway or other change of section which may be used as a reference. A drawing or simple sketch may also be used to indicate the location at which the transfer was taken.

Common Applications

Inspection of Heavy Weldments.—Magnetic particle inspection may be applied to all types of heavy weldments, as long as the materials are magnetic. It is usually used to inspect the finished welds. On heavy, multiple-pass welds, however, it is sometimes used to inspect each pass immediately after it has been deposited. It is also often used to inspect roots of joints which have been back chipped, in order to be certain that the weld metal has been removed to sound metal and that no cracks are present. Where the weldment is to be stress relieved, it is usual to make a final inspection after stress relieving. It is possible to obtain greater sensitivity for detection of subsurface defects after stress relief and there is also the possibility that small subsurface cracks may be extended by the stress-relief treatment. In some cases it may be advisable to inspect both before and after stress relieving

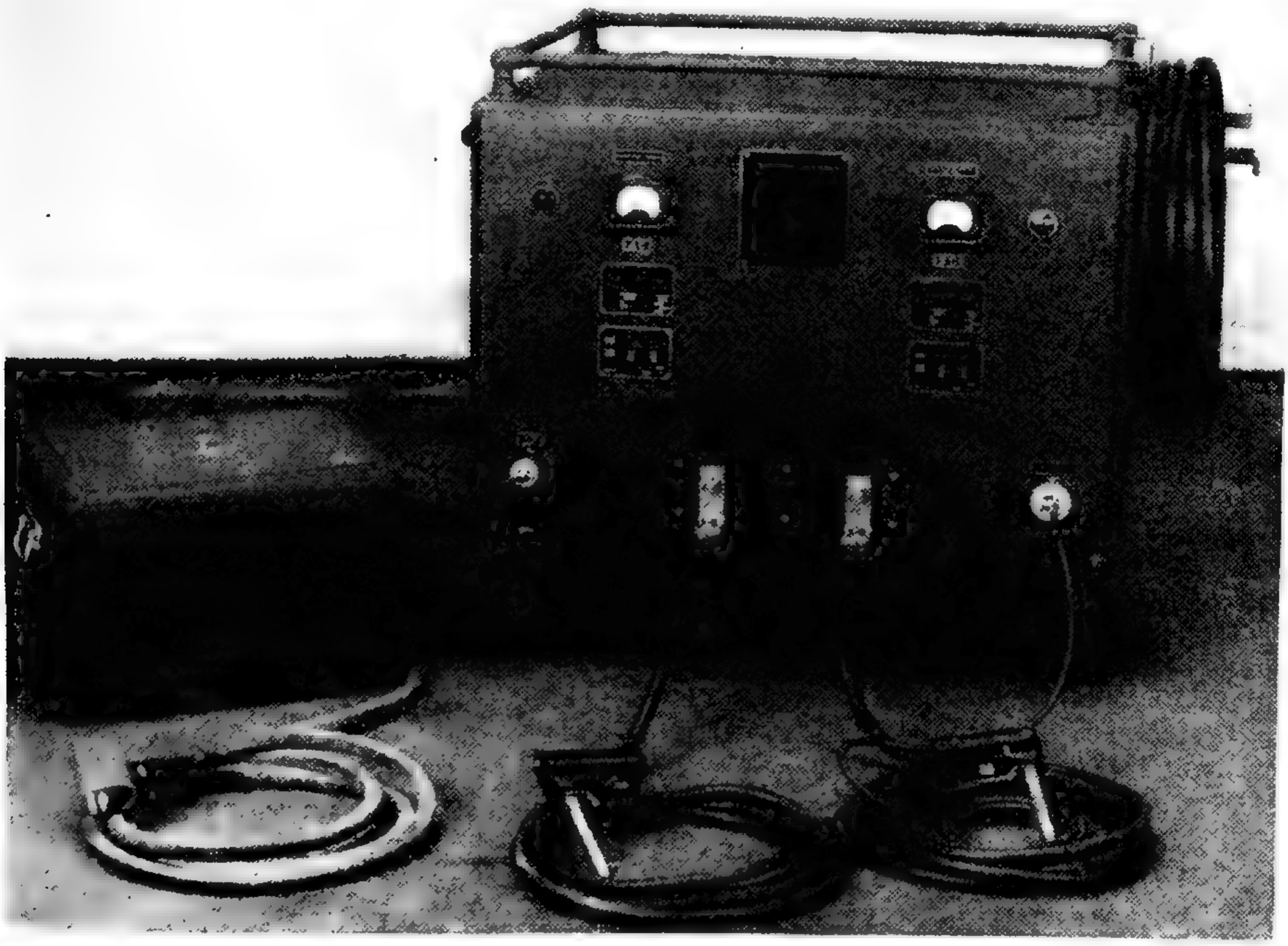


Fig. 44.—Typical Portable Equipment

Includes powder blower and contact prods. Suitable for inspection of heavy weldments by dry method.

so that major repairs can be made before stress relieving.

The dry continuous method using some type of direct current and employing local circular magnetization (prod technique) is usually recommended for heavy weldments. Half wave, rectified current is preferable for location of subsurface discontinuities. Alternating current may be used if inspection is to be limited to detection of cracks extending to the surface. The weld is magnetized by passing about 600 to 1000 amp. along the length of the weld using a prod spacing of from 4 to 8 inches. The prod positions should be overlapped slightly on consecutive shots.

Inspection of Light Weldments (Aircraft Type).—Most steel weldments used in aircraft are inspected by the magnetic particle method. These parts are subjected to fatigue conditions which means that location and elimination of all surface cracks is particularly important. Also since the weldments are relatively thin, magnetic particle inspection offers ample sensitivity to detect any subsurface discontinuities which might be detrimental. Light, aircraft-type weldments are usually inspected by the wet continuous method. Direct current is usually used although alternating current has been found satisfactory on thin materials. The continuous method is usually recommended even though many of the alloys commonly used in aircraft structures have fairly high retentivity.

Small weldments which can conveniently be inspected by the overall method on standard, stationary type units are given two inspections using both longitudinal and circular fields. Larger weldments are inspected by local circular magnetization. This is accomplished by making contact to the structure with fishmouth clamps or some other suitable contacts. A longitudinal field may be used on large structures by wrapping several turns of cable around the weld area.

Plate Inspection.—Magnetic particle inspection is frequently used to inspect plate edges prior to welding. The purpose of this type of inspection is to detect cracks, laminations, inclusions and segregations. It will only reveal those discontinuities which are near or extend to the edge being inspected. Not all discontinuities found on plate edges by magnetic particle inspection are objectionable. It is necessary, however, to eliminate those that would either affect the weldability of the plate or the ability of the material to assume design loads under service conditions.

The dry continuous method, employing prod technique with either a.c. or d.c. is suitable for plate edge inspection. When a.c. is used, the inspection is limited to discontinuities extending to the edge being inspected.

Repair or Rework Inspection.—One of the most useful applications of magnetic particle inspection is in conjunction with repair or rework procedures both on new parts and on parts that may have developed cracks in service. This applies not only to repair of weldments but also to rework done by welding in the repair or salvage of castings and forgings. Many objectionable discontinuities which have been detected by magnetic, radiographic, visual or other inspection methods, may be removed by chipping, gouging or grinding, and the repair made by welding. In this type of work it is useful to inspect the cavity after the defective material has been removed to make certain that the discontinuity has been entirely eliminated before proceeding with the repair weld. It may also be advisable to check the repair weld itself after it has been completed to find any cracks or other objectional discontinuities in the weld or in the adjacent metal.

In general the same inspection procedures should be used in connection with repair or rework procedures as would be used on the original parts.

FLUORESCENT PENETRANT INSPECTION

General

Fluorescent penetrant inspection is a non-destructive test method for locating cracks, pores, leaks and similar discontinuities in solid materials. It is particularly useful on non-magnetic materials where magnetic particle inspection cannot be used. Its principal uses in the welding field are for the detection of surface defects in aluminum, magnesium and austenitic steel weldments, and for locating leaks in all types of welds.

Since variations are possible in inspection techniques, and in the evaluation of the results, it is essential to predetermine what welds are to be inspected, the exact technique to be used, what types of discon-

tinuities are to be rejected, and what rework will be permitted. Since this method depends on producing, recognizing and evaluating visual indications, its success or failure depends primarily on the care and knowledge of the inspector.

Basic Principles.—Fluorescent penetrant inspection makes use of a water-washable penetrant of high fluorescence and unusual penetrating properties. Due to its low surface tension, it will readily be drawn into extremely small surface openings by capillary action. It carries a dye in solution which will fluoresce brilliantly, even in minute quantities, when exposed to near ultra-violet or black light.*

After proper washing, drying and developing, the discontinuities are shown by brilliant fluorescent indications when the part is examined under black light.

Technique

Penetration.—A surface film of penetrant is applied to the areas being inspected by dipping, brushing or spraying. The required penetration time may vary from one minute to several hours depending on the material and type of defect. Heating the penetrant is not recommended. Since it is necessary for some of the penetrant to enter the discontinuity in order to produce an indication, the part must be clean and dry before inspection.

Rinse.—After penetration all traces of penetrant must be removed from the surface by a water rinse. This operation should be done under black light to assure a rapid and complete operation. It is best accomplished by a special low-pressure water spray. It may also be accomplished with clean water-soaked rags, or by sand blasting. Solvents should not be used as they may remove indications of discontinuities.

Develop.—Dry developer is applied to the surface after drying. The drying may be accomplished by a hot-air dryer, by a blast of clean dry air or by standing in air. Dry developer may be applied with spray bulb or powder gun or by dipping small parts in the powder. After application of the dry developer a developing time should be allowed of about half the penetration time.

Wet developer is applied to the surface in the form of a colloidal water suspension. This is done after rinsing and before drying. It may be applied by dipping or spraying. Hot air drying is recommended. No additional developing time is necessary since the indications are developed during the drying operation.

Inspection.—The actual inspection is conducted under a fixed or portable black light with all other light subdued. This may be in a booth or shaded area in the plant. The indications fluoresce brilliantly and a deep discontinuity may be distinguished from a shallow one by the width or amount of fluorescent bleeding of the indication.

Common Applications

Large Weldments.—Pressure and storage vessels and piping in the petroleum, chemical and dairy industries are often made of non-magnetic materials and may be inspected for surface cracks and porosity by this method. The penetrant is usually applied to the clean dry surface by brushing or spraying. For usual conditions penetration time is about one hour. Dry developer is normally used because hot air drying is impractical. Sand blasting instead of rinsing is excellent when available, since its use eliminates the necessity for drying, and the fine particles of sand act as developing material.

Small Weldments.—Small aluminum, magnesium and austenitic steel weldments for such applications as aircraft and jet engines and welded valve facings are usually inspected using standard stationary equipment. Penetrant is applied by dip or flow-on techniques and penetration times of from 30 min. to 2 hr. are allowed. Wet developer is usually used because of its ease of application to complex shapes. A hot air dryer is recommended for maximum sensitivity.

Lined Vessels.—Fluorescent penetrant may be used to quickly and effectively detect cracks, pores and leaks through the lining in lined or clad vessels of the type used in the petroleum and chemical industries. It may be applied to all types of welded linings. The techniques are the same as for large weldments. Shallow cracks and porosity may be distinguished from those that extend through the lining (*leakers*) since the indications of leakers

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* *Black light* is the term applied to the invisible, near ultra-violet light, about 3650 Angstrom units in wave length, or just beyond the visible spectrum. It is usually obtained from a high-pressure mercury-arc bulb equipped with proper filter.

spread rapidly or *bleed* upon application of dry developer.

Leak Testing.—One of the simplest and most useful applications for fluorescent penetrant inspection is for leak detection. It is used for checking both magnetic and non-magnetic weldments, and may also be used on brazed joints. The procedure is to apply the fluorescent penetrant to one side of the joint, by brushing or spraying. The penetration time depends on the type and thickness of the joint. The other side is then examined using a portable black light. Dry developer may be used on the side being inspected to intensify indications. No pressure is necessary since the penetrant is drawn through the leak by capillary action. It is particularly effective on thin-walled vessels and will find leaks not found by the usual air test with pressures of 5 to 20 psi. The sensitivity of the leak test drops off on materials over $^1/_4$-in. thick.

RADIOGRAPHIC INSPECTION

General

Radiography is a nondestructive test method which shows the presence and nature of macroscopic defects or other structural discontinuities in the interior of welds.

This test method makes use of the ability of short wave radiations, such as X-rays or gamma rays, to penetrate objects opaque to ordinary light. In general, the shorter the wave length, the greater the penetrating power. Not all of the radiation penetrates the weld, some being absorbed. The amount of this absorption is a function of the density and the thickness of the weld. Should there be a cavity, such as a blowhole, in the weld interior, the beam of radiation will have less metal to pass through than in a sound weld. Consequently, there will be a variation of the absorption of the rays by the weld in the defective region which variation, if measured or recorded on a film sensitive to the radiation, produces an image that will indicate the presence of the defect. The image is an X-ray shadow of the interior defect. Such a shadow picture is called a *radiograph.* A successful radiograph will be one which has so faithfully recorded the X-ray image that the presence or absence of a defect in a weld is established and, if present, its size, shape and location are clearly defined.

Radiography like most tools has certain limitations and its correct understanding, application and interpretation require a technical knowledge of the method, and a reasonable conception of the type of the defects disclosed and their relation to the applicable specification.

Sensitivity as Measured by the Penetrameter.—It is generally assumed that radiographic methods will produce films having a sensitivity of 2%. When sensitivity is spoken of, it is considered to mean the least percent of weld thickness difference which can be detected visually on a radiograph. The detection of such a thickness difference by the observer is a function of the sharpness of the outline of the image and of the contrast of the image against the film background. For the detection of these two qualities in a radiograph a gage known as a *penetrameter* is used. The ASME *Boiler Code Penetrameter* consists of a thin strip of metal equal in density to the weld metal. Its thickness is equal to or less than 2% of the weld thickness. Lead numerals are attached to one end, which indicate the thickness for which the penetrameter is to be used and three holes are drilled in its face, the diameters of which are equal to certain percentages of the weld thickness, as for example, 4, 6 and 8%.

The penetrameter is placed on the side of the weld away from the film. The appearance of its image on the film is studied as an indication of the two film qualities, sharpness and contrast, described above. In some work the penetrameter is used primarily for the determination of image sharpness and is therefore not considered a complete measure of film quality. Just what these qualities mean to the inspector is outlined in the following two paragraphs.

Sharpness of Image Delineation.—This is determined by the relative sharpness with which image details of the penetrameter are shown on the negative for a given type of radiographic film.

This information furnishes evidence as to negative quality. That is, fine detail, such as a fine crack, if sharply defined is more easily detected in the negative. Also sharp image delineation is an indication of whether or not certain factors of the radiographic procedure were correct. That is, fuzzy images could be caused by a vibrating source of radiation or by

an improper working distance. Sharpness of detail is very important for proper interpretation of the radiograph. There are numerous factors affecting it which are pointed out below.

Contrast.—This may be defined as the ease with which an image can be seen against the negative background. It is determined by the relative density of the image as compared with that of the adjacent film. Several factors control contrast, the two most important being the kind of radiation and the type of film used. For example, if a weld containing large and small defects is radiographed using the same type of film and exposure to produce the same background density, first with 200-kv. X-rays and then with million-volt X-rays, the individual images in the first negative will be denser than those of the second and there will be a greater spread between the highest and lowest density in the first than in the second negative. The one taken with 200 kv. is said to have more contrast than the one taken with the million-volt X-rays. Besides the kind of radiation and film type, other things such as exposure, extraneous radiation, film processing, etc., may affect contrast. It is obvious that the optimum contrast for the negative requires an adjustment of factors for the particular type of defect that is of most interest to the inspector. Often certain conditions may exist which in one way or another prevent an ideal combination and result in certain limitations. For example, if a weld which is at the top limit of the penetration range for a particular X-ray machine must be radiographed, it becomes necessary to use faster, coarser-grained film than would be necessary if another machine were available. This results in lower contrast because of a greater quantity of extraneous radiation affecting the film due to the long exposure required and the greater sensitivity of the film used for this type of radiation.

Significance of Penetrameter Image.—While the penetrameter has been used as a sensitivity gage its effectiveness for this purpose has been questioned. Most skilled operators prefer to rely upon internal evidence in the film itself. It is very useful however, to the inspector. From a study of the penetrameter images he can obtain information as to sharpness of image delineation and photographic contrast. Such information is of great value in interpreting negatives. In addition, the presence of the penetrameter image constitutes evidence that can be used perhaps years later in determining whether or not the film was properly made. This point is of particular importance where inspection negatives may be used in studies to determine causes of failures that have occurred in service.

One of the most troublesome problems with some types of metal is that of uniformity of radiographic interpretation where X-rays are used on some pieces and radium on others. Because of this problem some further consideration of the effect of the type of radiation used on contrast is justified.

The wave length of the radiation from radium sources is very short and, in consequence, the contrast obtainable is much less, factors other than radiation being constant. There is a tendency to underexpose gammagraphs because of the long time required in making exposures. Low contrast, as indicated by the penetrameter images, coupled with light film density means almost certain loss of fine image detail. However, there is some compensation in the use of short wave length radiation. That is, since contrasts are lower for short wave length radiation, a wider range of defects of varying depth dimensions can be shown on the same negative. This is due to the fact that the latitude of the film is itself limited. Hence if the exposure is such as to bring the penetrameter image to a density comparable to that found in the film taken with longer wave length radiation, the one taken with the shorter radiation should show, theoretically, as much detail as the other although the contrast gradation will be less and the negative will appear flatter. However, the images of details that were faint in the first picture will be lost in the second one because of the low contrast. So that for practical purposes while the apparent latitude of the negative has been increased, its sensitivity, as measured by its ability to depict very small defects, has not been maintained.

It is to be emphasized that in comparing radiographic results obtained with X-rays and radium it is necessary that the two radiographs involved be exposed to produce, with full development, the same background density. Some modification of

this may occur where different types of films are used, but until the inspector has had sufficient experience to make this allowance intelligently he should insist on the same background density and this should be high. With the film so exposed and developed, allowance must be made for the difference in contrast levels that will be present. That is, the inspector must know what contrast to expect from the type of film and the kind of radiation used. There seems to be no substitute for actual experience in the determination of proper allowances. However, most of the difficulties in uniformity of interpretation disappear where high-density negatives are required and where the X-ray and the radium films are exposed to approximately the same background density.

shown on a radiograph is usually of irregular shape. The image of a typical slag inclusion is shown in Fig. 45.

Porosity.—The images of porosity or gas pockets in a weld as shown on a radiograph are usually small dark spots. These images may be fine or coarse, they may be widely scattered or closely grouped. A typical porosity image is shown in Fig. 46.

Cracks.—Cracks in welds produce film images of a line darker than the film background. Because they extend primarily in one plane some of them require the best technique to properly produce a satisfactory image on the film. This is particularly true where the plane in which they lie is not parallel to the X-ray beam as, for example, a crack following the dendritic structure of some welds. A typical crack as shown by radiography is illustrated in Fig. 47.

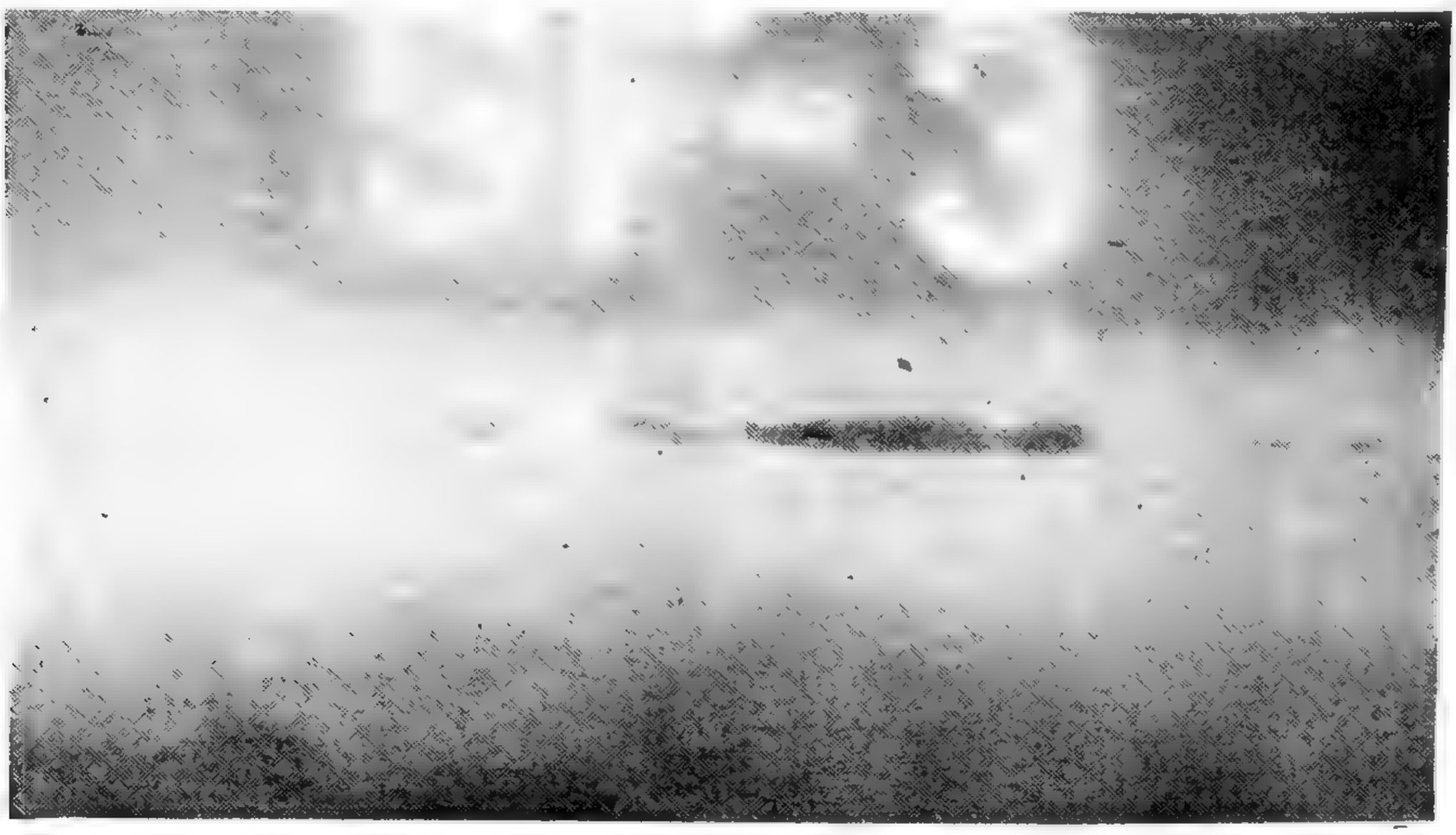


Fig. 45.—Radiograph Showing Fusion Zone Slag

Other Defects.—The images of other defects common to arc welding are shown in Figs. 48 and 49. These include inadequate penetration, undercut, surface defects and incomplete fusion. The inspector's ability to recognize these according to type is largely a matter of experience and his acquaintance with standards.

What Radiographs Will Show in a Weld

There are a number of types of defects common to arc welding, the presence of which may easily be shown by means of radiography. The cause and description of them are given elsewhere in this HANDBOOK. The purpose of this section is to describe and illustrate how images of typical welding defects appear in radiographs. It will also describe briefly how specifications treat these defects from the standpoint of acceptability.

Slag (Nonmetallic Inclusions).—The image of a slag inclusion in a weld as

Viewing Conditions

For the proper interpretation of a radiograph it should be examined under con-

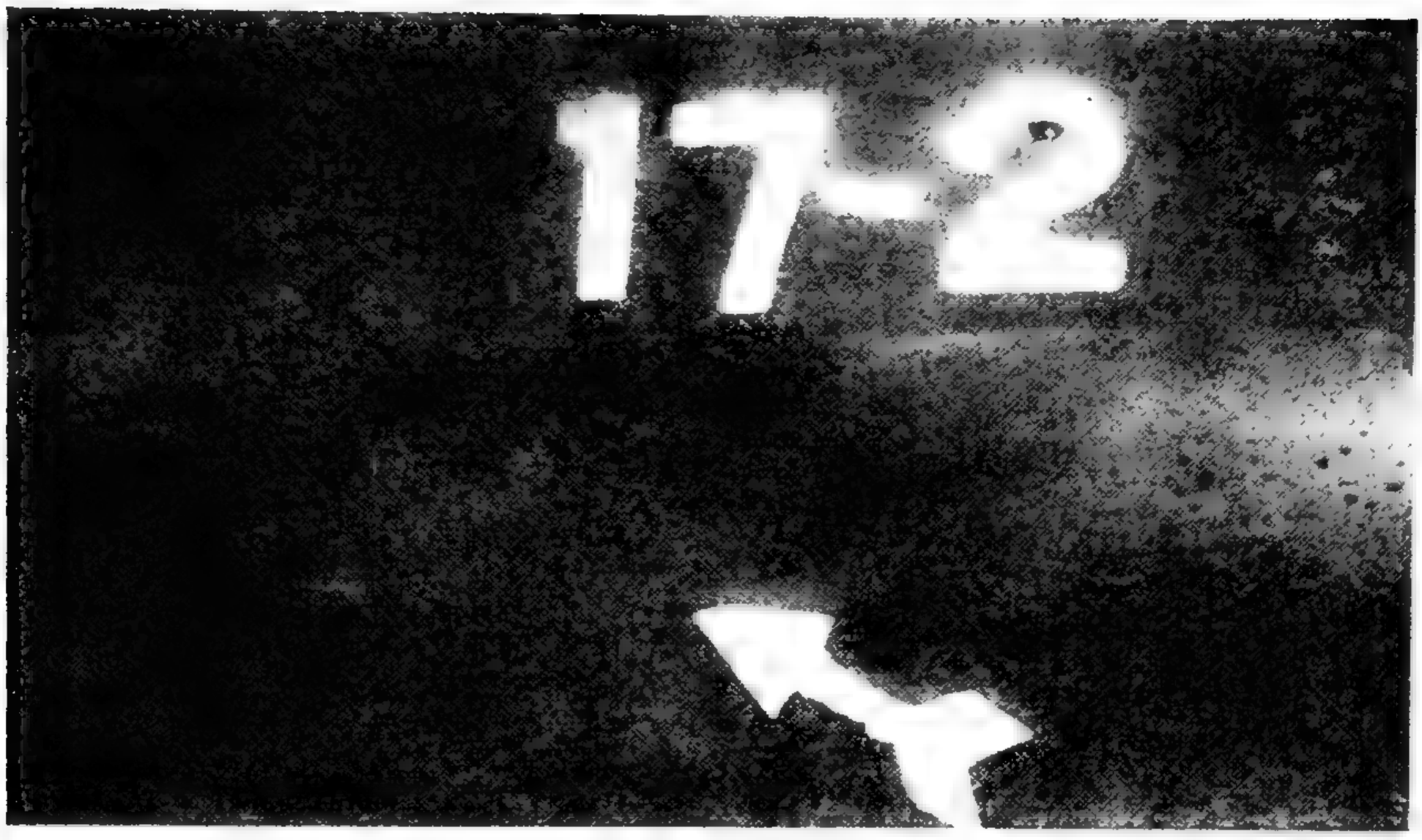


Fig. 46.—Radiograph Showing Porosity

ditions which favor the best visualization of detail combined with a maximum of comfort and minimum fatigue for the observer. Radiographs of welds usually have low subject contrast.* Consequently, satisfactory examination of films of welds can usually be made with a single intensity illuminator. The viewing box should be situated in a special viewing room which is darkened and well ventilated. It should have sufficient intensity to permit the examination of the darkest areas of the film without strain to the observer. The color of the light has no actual optical significance although some people prefer the light to be green or blue.

The illuminator should provide a cold light or should have forced ventilation so that its heat will not curl the films placed against it for viewing and so that there will be a minimum of discomfort. Fluorescent lamps provide satisfactory cold light sources. Ventilated illuminators using high-intensity incandescent lamps with rheostat controls are commercially available. The variable intensity obtainable from such units is of particular advantage in viewing high-density negatives.

The light should be provided with a means of cutting off the extra area beyond

* By subject contrast is meant the ratio of X-ray intensities transmitted by different selected portions of the specimen. A casting having abrupt thickness changes would have high subject contrast.

Fig. 47.—Radiograph Showing Cracks

that of the film and a means of clamping or resting the film against the ground-glass face. It should be placed on a table at eye level so that the viewer may sit erect.

Film-Processing Marks

An inspector of radiography must have the ability to interpret films. This ability is largely obtained through experience. However, there are certain fundamentals which may be of help.

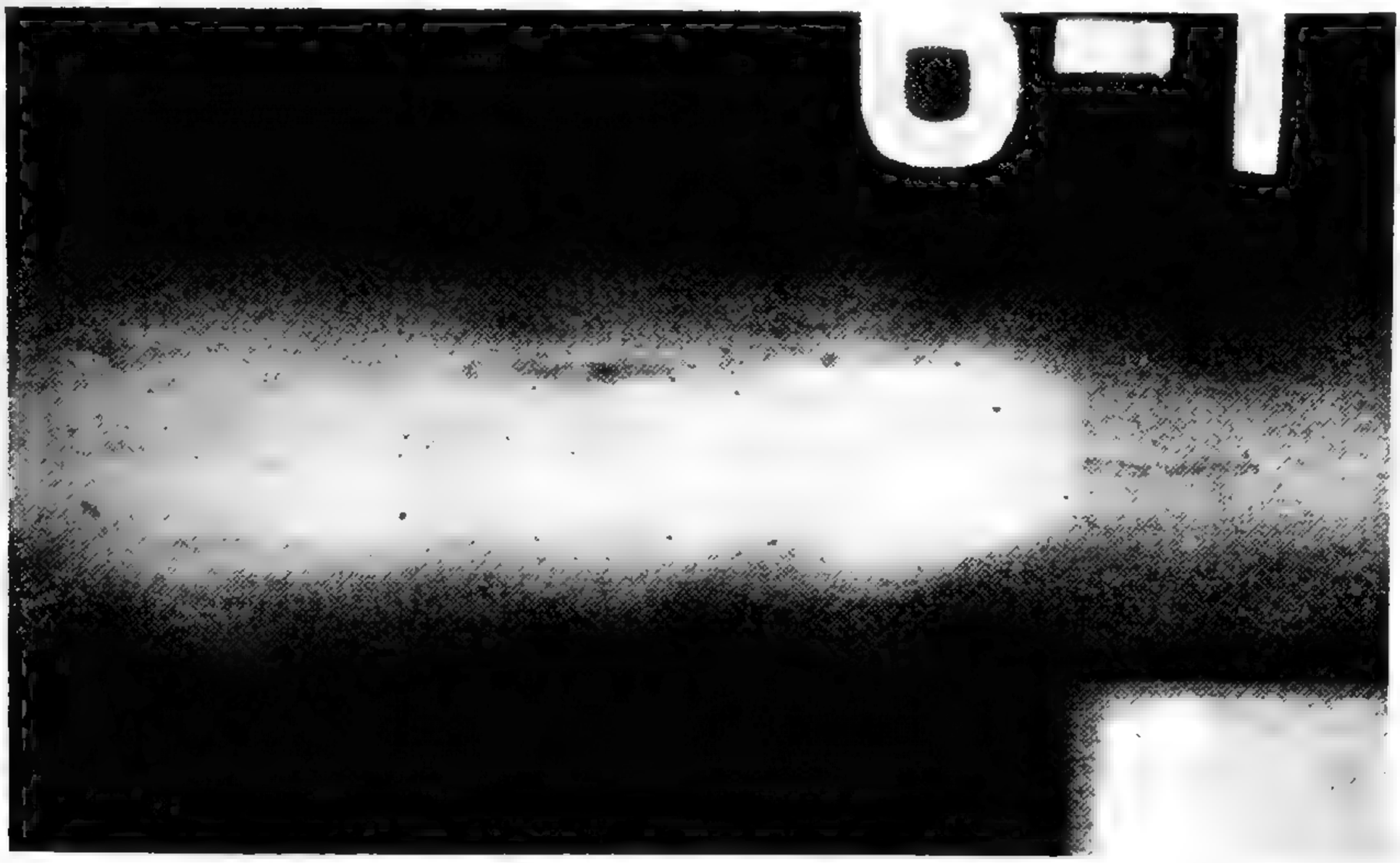
Modern X-ray film consists of a special emulsion, a gelatin that contains a silver halide compound, coated on both sides of a cellulose base. When the film is exposed to X-ray, a change takes place in the silver halide salts; those that have been exposed to radiation are capable of being converted into another form of silver by the chemical action of a solution called the developer; those that are unexposed by the radiation can be removed by the chemical action of another solution called the fixer. When we speak of *processing a film* we mean the various steps of developing, fixing, washing and drying the film. When film processing is carried on by means of a standardized procedure, carefully followed in every detail for every film, clear and satisfactory films result. Often it is found that variations from a set procedure are made and that these result in marks on the radiographs. It is the duty of the inspector to recognize these marks, to understand when they interfere with the proper interpretation of the film and to call for re-X-ray when necessary.

Processing defects, spots and marks on radiographs of many kinds may be experienced. For example, colored stains or blisters may be the result of an improper wash and stop bath between the developing and fixing solutions. Streaks may be the result of improper agitation of the film during development. Stains may occur because of improper mixing of solutions or because of the use of solutions past their exhaustion point. Static marks, which look very much like a crack system, are often seen on films developed on damp days and are caused by careless handling. Streaks may re-

Fig. 48.—Radiograph Showing Inadequate Penetration

sult from too long viewing of the wet film before a safelight lamp when it is saturated with developer solution. Chemical fog may be caused by too long developing times. Many other processing defects are known. An inspector may gain further knowledge of them by reference to any of the processing manuals published by the various film manufacturers.

absorptive material, such as lead sheet, it will be exposed by *back scatter*. This is usually indicated on the film by images of the steel clips of the cassette. If the undeveloped film is pinched between the finger ends during loading and unloading of the cassette, a characteristic film mark results. If too great a localized pressure is made against the film cassette during



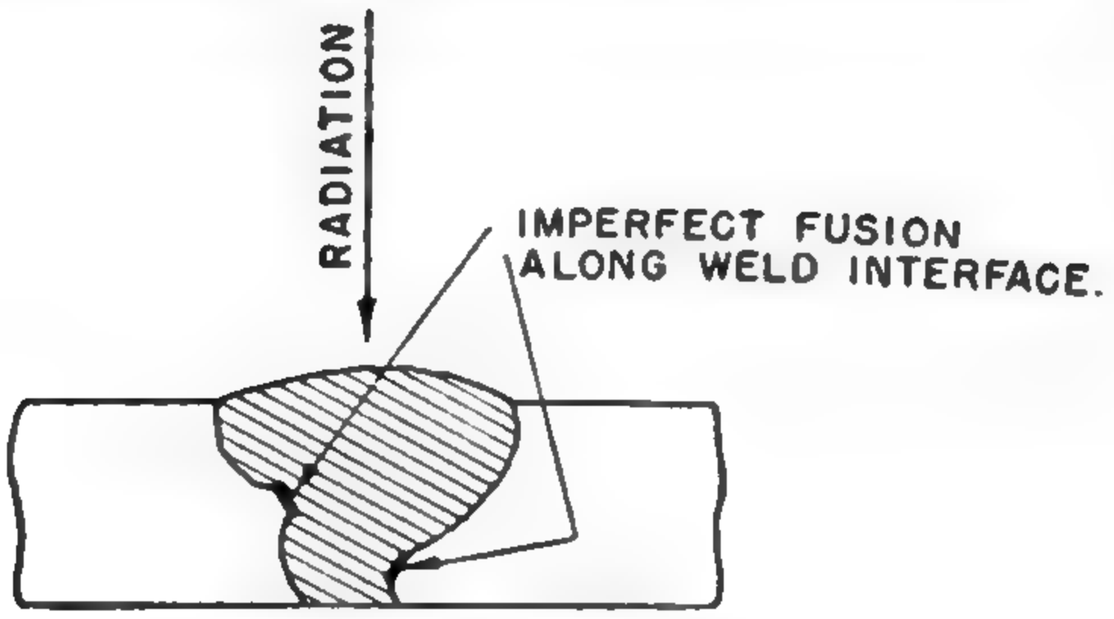


Fig. 49.—Radiograph Showing Incomplete Fusion

Film-Handling Marks

Besides processing marks, other film defects are the result of improper handling of the film. For example, fine mechanical scratches often occur during processing which, upon examination of the film, may be interpreted as weld cracks. Viewing the film surface by means of reflected light will show such marks as emulsion scratches.

If the film is not fully protected from the back during its exposure by a highly

exposure, film marking occurs. Poor screen contact (screens are intensifiers of the radiation, which are used in the cassette against the film to reduce exposure time), dirty screens and cracked screens result in film marks and unsatisfactory films.

Secondary Radiation Effect on Film Interpretation

Besides the primary radiation which forms the useful image on the film by

passing from the X-ray target in straight lines through the weld, there is set up in the weld an undirected radiation called *secondary radiation*. This action occurs when X-rays penetrate an object in a manner similar to the way in which light is scattered by fog. Since this radiation also affects the film, its undirected nature will produce a haze on the radiograph causing a loss of detail and contrast. As the thickness of the weld increases, so does the effect of the secondary radiation. There are a number of ways to control this condition, such as the use of slower, fine-grained films, lead screens or grid diaphragms.

Weld Surface Condition vs. Weld Defects

An inspector must be able to distinguish between images of weld surface markings and those of welding defects. It is, of course, obvious that this may be accomplished only by a familiarity with every detail of the fabrication of the job. In this connection it is also necessary to understand the angulation of the exposure, that this has been carried out as specified and that such angulation is given consideration in the interpretation of the radiographs.

X-Ray Source

The most common source of radiation for radiographic examination is an X-ray tube. This tube consists of an evacuated glass bulb in which are mounted two elements. One of these, the *cathode* or *filament,* is a source of electrons while the other is usually, for industrial X-ray work, a tungsten disk mounted in copper which is known as the *anode* or *target.* When the filament is heated it gives off electrons which are forced to travel across the space between the cathode and anode at high velocities by means of a high voltage. The higher the voltage, the greater the electron velocity and the greater the energy of their bombardment on the anode or target. The anode, as a result of this electron bombardment emits X-rays. These X-rays depend for their characteristics upon (1) the kind of material making up the target; (2) the number of electrons per unit of time striking it; and (3) the velocity of impact of the electron against the target.

These three characteristics are of great importance in the production of the radiographic film image. The first, of course, cannot be controlled by the operator of the machine. The second is known as the X-ray beam intensity and is varied by changing the filament temperature. A meter on the control stand of the X-ray machine which reads milliamperes controls the amount of electrons passing through the tube and may be adjusted by the filament regulator. For example, a machine operating at 5 milliamperes will produce an X-ray beam one-half as intense as when operating at 10 milliamperes. The third factor is controlled by adjustment of the X-ray machine voltage. This is usually accomplished by adjustment of the taps of an autotransformer of the machine. The high-voltage transformer changes line voltage to high voltages of, for example, 200,000 volts (200 kv.). The voltage across the tube adjusts the X-ray wave length and penetrating power. For example, a tube operating at 100,000 volts will produce X-rays which are less penetrating than one operating at 200,000 volts.

Gamma-Ray Source

Gamma rays are similar to X-rays except for their wave length which is shorter than most X-ray wave lengths, except those produced at one million volts or higher. The most practical source of this radiation is the atomic disintegration of radium. The quantity of radiation is proportional to the amount of radium used. For example, 100 mg. of radium requires twice as long as 200 mg. to satisfactorily radiograph a thickness of steel.

Radium, usually in the form of radium sulfate, is sealed in a small capsule. The cross-sectional area of the capsule containing the radium corresponds to the focal spot size of the X-ray tube.

While the short wave length of gamma rays allows the penetration of considerable thickness of material, exposure times required are usually many times longer than for X-rays because of the lower intensity of the source. The low contrast levels obtainable with gamma rays render them unsuitable for most weld inspection.

X-Rays vs. Gamma Rays

It is not easy to compare the merits of X-rays and gamma rays as a source of radiation for radiography. Each has

a definite application in its own fields with one hardly a substitute for the other. Because of the lower absorption coefficient of gamma rays as compared to the longer wave length of X-rays the general rule is that lower contrast negatives will result. The lower intensity of this radiation as compared to that obtained with X-ray equipment makes necessary the use of long exposure times, which are not always practical or economical. Shorter exposure times with sacrifice of sharp definition may be obtained by using shorter working distances. This loss of definition may be compensated for to a certain extent by the use of fine-grained films especially sensitive to gamma-ray radiation. One expedient that has been used to overcome the low contrast obtained, is the simultaneous exposure of duplicate films, the resulting negatives being placed in contact for reviewing. Contrast in the negative is improved by developing to the limit possible before the incidence of chemical fog.

Where the exposure is sufficient to yield high-density negatives (above 2.25 H and D), image details that are faint and readable only with difficulty or not at all become much more easily discernible when viewed with suitable illumination. The high-density procedure can be applied to gamma-ray and high-voltage X-ray negatives more successfully than to radiographs made with low- or medium-voltage machines because of the lesser influence of secondary radiation in the former cases which contributes to film blackening, but not to image delineation.

Gamma rays, like high-voltage X-rays, are found to be extremely valuable in radiographing materials having high subject contrast. The principal advantage of this source of radiation is that it is extremely portable.

High Voltage X-Ray Sources

In recent years X-ray equipment has been developed to where the range of energy available is extended indefinitely, the only limit being the size of the machine. This development began in 1941 with 1000 KVP* X-rays. During the war 2000 KVP was successfully used and is now applied successfully in industrial applications. Figure 50 shows a 2000 KVP machine which represents the practical limit where X-rays may be generated by the direct application of accelerating potentials. This limit has been overcome by means of the development of the Betatron which accelerates electrons by means of magnetic induction. In this instrument an alternating magnetic field holds the electrons in a stable circular orbit within an evacuated annular chamber. An increasing field produces a force on the electrons which accelerates them to high velocities. After the electrons achieve a certain velocity they are ejected from their orbit to strike a target at which X-rays are generated. The Betatron is used successfully for radiographic examination. The most successful field is for heavy sections, particularly where there are sharp variations in thickness.

X-Ray Exposure Factors

The successful exposure of a radiographic film is a function of several factors, some of which have already been pointed out. These are:

(*a*) Wave length (tube voltage).
(*b*) Intensity (milliampere setting).
(*c*) Source-to-film distance.
(*d*) Thickness of the material.
(*e*) Density of the material.
(*f*) Size of the source (focal spot).
(*g*) Time of exposure.
(*h*) Type of film.
(*i*) Type of screen.

It is necessary to control and adjust these factors to obtain a combination which gives an X-ray beam of sufficient intensity and absorption characteristics to properly expose the film. Some of these factors are directly controlled by adjustment of the X-ray tube current, the X-ray source to film distance and the time of exposure. The voltage, the current and the time of exposure are all directly proportional to the total X-ray beam energy. That is, an increase in any one or all of these three factors will increase the X-ray energy accordingly. The X-ray energy will also vary inversely as the square of the X-ray source to film distance. That is, as this distance increases the X-ray beam intensity will decrease very rapidly.

The best technique, then, is the one which combines all of these factors so that a film having the highest definition is obtained. This does not necessarily mean the use of the highest voltage, the

* Kilovolt peak.

shortest time, etc., but is best determined by trial exposures.

X-ray Films

The emulsion used for X-ray films is different from that used on other photographic film. There are a number of types of film available for industrial radiography to meet the different conditions encountered. These films are generally classified according to the emulsion grain size and according to the type of intensifying screen with which they are to be used.

In general, there is a relationship between the speed of the film (length of exposure time required) and its graininess; the faster the film, the more grainy it becomes. Likewise, for a given film, the higher the voltage, that is, the shorter the X-ray wave length, the more grainy the film after development.

Early medical and industrial radiography employed X-ray films whose emulsion was only moderately sensitive to a blue-green fluorescent light given off by calcium tungstate when irradiated by X-rays. This material, when used as intensifying screens, results in a very fast exposure with very high contrast. The light from the intensifying screen diffuses within the active layer of the screen, and while films exposed with this technique have a high image contrast, the definition or outline of images is relatively poor. The type of film used with these screens is also more sensitive to direct exposure from soft, that is, long wave length radiation than to hard, penetrating rays. As a result, when heavier sections are being radiographed scattered radiation, which is of longer wave length than the primary beam, is recorded on the film and results in loss of detail and contrast. It is used satisfactorily for radiographs of welds. However, it is the general opinion today that for most work the type of film which is more sensitive to direct exposure by X-

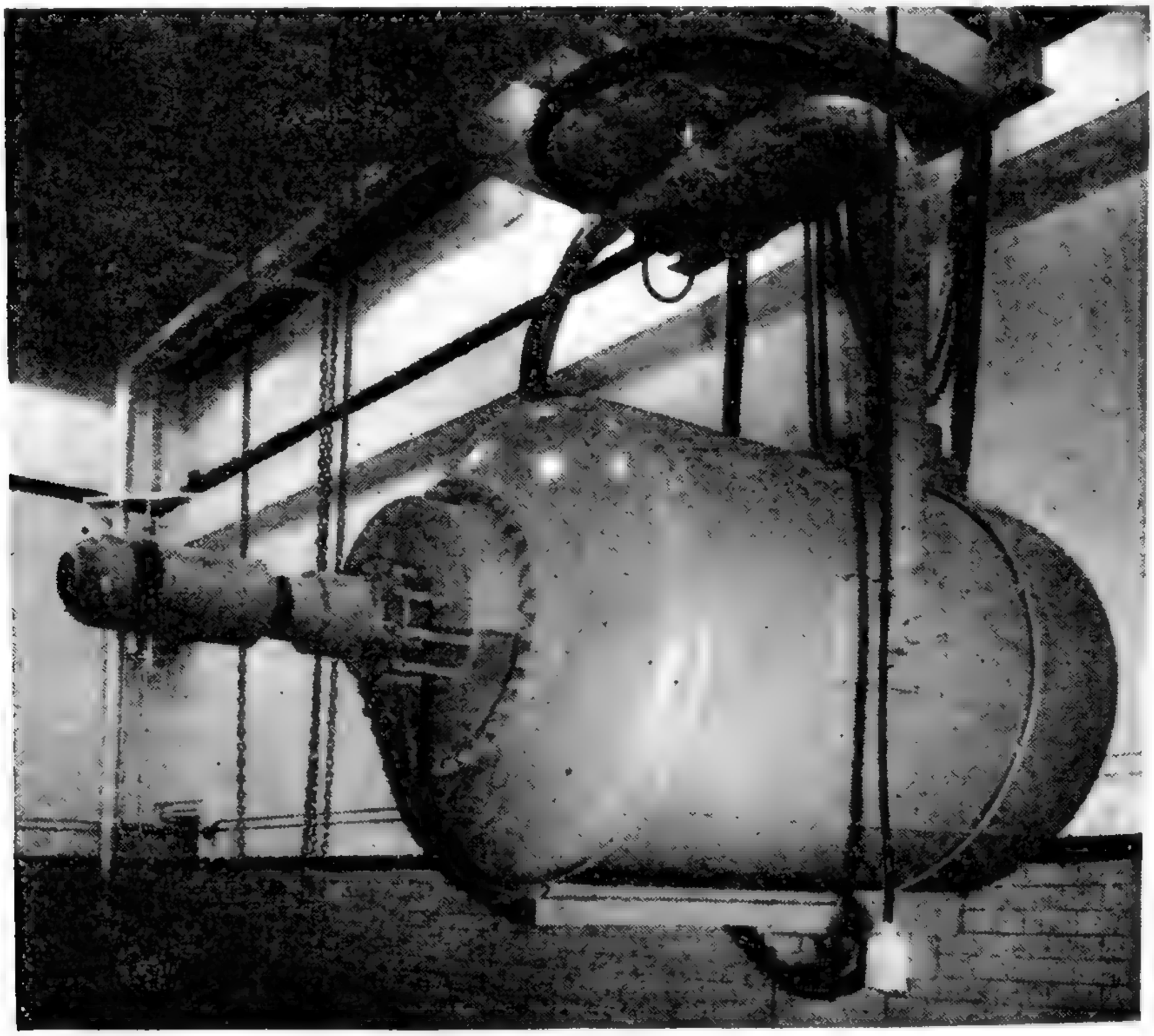


Fig. 50.—2000 KVP X-Ray Machine

rays and known as *no-screen* or *direct exposure* type film gives improved results. However, the extent to which no-screen film may be applied practically depends upon the type of X-ray equipment available and the voltages of operation; the shape and thickness of the weld being examined; and geometric considerations such as film distance, weld location, etc.

The no-screen type film has the disadvantage of being slower than regular-screen film. It must be used at higher voltage ranges and unless the X-ray equipment available has a sufficient voltage range to accomodate it, the practical application of this type of film to all work may prove difficult.

Density of Exposure of Radiographs

When X-rays or gamma rays penetrate an object and reach the film they form a shadow image on the film. This image appears first because the differential absorption of the radiation by the object allows different intensities to reach it; second, when this radiation strikes the film it causes a physical change to take place in the film emulsion. The degree or amount of this change is a function of the amount of radiation absorbed by the emulsion. This in turn depends upon the amount of radiation striking the film, its wave length, and the characteristics of the emulsion. The incident radiation is proportional to the time of exposure and the current through the X-ray tube, that is to the product of the exposure time and the current through the tube. This product gives the exposure. When the film is processed the areas of the film at which the emulsion has undergone physical changes due to the radiation exposure turn black, the density of these blackened regions being in direct relationship to the exposure.

The relationship of exposure and film density is used to plot what is known, for each type of film, as the characteristic film curve. This curve is a function of the relationship between the film density and exposure. The negative density is defined as a function of the opacity, which in turn is defined as the ratio of the light incident upon the negative to that passing through it. Density values thus determined are expressed in *H and D* units (after Huerter and Driffield who originated the characteristic curve). Density values for different images in a photographic negative may run from 0.1 to 3.0 H and D, 0.1 being too faint for easy detection and 3.0 being opaque to a moderately bright light, but transparent to very strong light.

In practice, densities are determined usually by direct comparison with negatives of known density. They may be determined by photometric measurements of the incident and transmitted radiation. Negatives of measured density are used by inspectors in estimating the density of radiographic inspection negatives. Here the comparison is visual, precise values not being required. It may be noted that since X-ray intensities are not measured directly but are expressed in terms of milliampere-seconds or milliampere-minutes, the characteristic, or Huerter and Driffield curve is based upon arbitrary units and indicates relative values only. This fact does not, however, detract from its usefulness since the arbitrary units are well established.

Geometric Factors

The sharpness or detail of the image of a defect as it appears on the radiograph is important because the eye detects an image of low contrast more readily if it is sharply defined. The sharpness of the image, while influenced by other factors, is greatly dependent upon the geometrical relationship of the size of the focal spot, the distance from focal spot to defect and from the defect to the film. The image sharpness is seen to improve (1) by use of a very fine focal spot; (2) by having the film as close to the weld as possible; and (3) by using a d/t ratio equal to a minimum of 20, where d is the distance from the focal spot to the tube side of the object, and t is the distance from the tube side of the subject to the film.

The plane of the defect and its relationship to the direction of the X-ray beam has an important effect upon radiographic results. For example, a fine crack whose faces are not parallel to the X-ray beam may produce a very faint image on the film because of the low absorption of the X-ray beam in the particular direction. If the defect is so located in the area under examination that its image is produced on the ends of the film, this image will be enlarged to a degree where it may

pay to take a more direct exposure. It is good practice not to expose too great a distance on one film.

Scattered and Secondary Radiation

Whenever X-rays strike any object they set up other X-rays from the object which are undirected, and scatter in every direction about the object. The film must be protected during exposure from this radiation. Since it can only reach the film from the back or edges, lead backing on the cassette will protect the film without influencing its exposure.

When X-rays penetrate an object they set up within the object itself a secondary radiation which, while longer in wave length, is just as effective in exposing the film as the primary rays. This radiation, however, is different from the primary radiation in that it is undirected and if allowed to reach the film it produces a hazy background which reduces film detail and contrast of the image.

This effect is not particularly evident until the weld thickness becomes greater than $1^1/_2$ in., and then it depends upon the technique employed. Several practical methods are available to reduce the effect of internal secondary radiation on the image. One is to employ a grid of lead strips between the weld and the film. The openings in this grid allow the primary or directed radiation to reach the film but at the same time block off the undirected secondary radiation. This device is known as a *Bucky grid*. Another method is to employ solid lead filters between the weld and the film. The filter is thick enough to absorb the undirected secondary but at the same time permit a reasonable percentage of the primary radiation to reach the film. The use of direct-exposure film in conjunction with lead filters is most effective. These films are not particularly sensitive to the longer wave length secondary radiation and consequently its effect is correspondingly decreased. Greater detail results and it is possible to obtain very high definition on films of heavy welds.

X-ray Protection

Any body tissues, if overexposed to radiation from X-ray machines or gamma-ray capsules, will be injured. Small amounts of exposure from day to day with insufficient recovery periods are cumulative and eventually may cause serious results. It has been shown, however, that the body can stand a certain daily tolerance dose, but precautions should be taken to avoid unnecessary exposure. Various methods such as *r* meters, film exposures, etc., are used as a check of stray radiation. (For more complete information on X-ray protection the American Standard *Safety Code for the Industrial Use of X-Rays* may be consulted.)

MECHANICAL TESTING

The mechanical inspection of welds is divided into two general classes, proof testing and destructive testing.

Proof Testing

Proof testing consists of applying a load or pressure equal to or exceeding that expected in service, but not great enough to cause damage to acceptable products. If tightness is the only consideration in the test, a pressure equal to the working pressure may be used. If the test is to determine strength or safety, the test pressure usually exceeds the working pressure. Experience shows that a vessel or other weldment that withstands a certain test pressure might fail later at the same or a slightly lower pressure. On the other hand failure is very unlikely at two-thirds of the test pressure unless there is some concentration of stress, as for example, a notch or defective weld, which might cause fatigue failure under repeated stresses.

The proof test force or pressure required to reveal defects that might later cause failure in service is a matter of judgment and experience. Its value is usually given in the specification or code governing the work. Many pressure vessels are hammer tested at $1^1/_2$ times the working pressure, and this is followed by a load test to twice the working pressure. Pipe fittings are often tested to $1^1/_2$ times the working pressure. The proof test pressure for pipe varies with its size, grade and wall thickness. Usually no assembly should be proof tested at more than the lowest test pressure specified for any of its parts. Thus, the specification test pressure for a valve or expansion joint may limit the proof test pressure of a pipe line.

To avoid damage to the weldment, the proof test should not develop primary

stresses in any part exceeding the yield point. To allow for uncertainties in engineering calculations, it is a good plan to limit proof tests to 75% of the calculated yield point. Secondary stresses, and the combination of residual stress with the proof stress may cause local yielding without damage. In fact, a proof test may act as a stress relief operation to a limited extent so that weldments may have their factor of safety under shock or low temperature stress actually improved by the stress relief resulting from proof testing.

Proof tests may not always reveal defects that might later cause failure. This applies particularly to stress raisers, like incomplete fusion at the root, under fatigue conditions or shock. It is quite possible under such circumstances for cracking under fatigue to occur later under the repeated application of a stress much lower than the test stress. Other methods such as radiographic inspection, etch tests or fracture tests must be used to avoid such defects.

Frequently, tightness is important in welded construction. Leaks are discovered by observation, or by loss of pressure in a tightly-closed vessel or pipe line. Oil, particularly thin or hot oil, will frequently penetrate leaks that do not show up with water under an equal pressure. Air also will leak out where water will not, and hydrogen will leak out where air will not.

When oil or water is used to apply the pressure, there is little difficulty in observing the leak on the low pressure side of a butt weld, if it is clean. A lap joint presents the problem that both the inner and outer fillet welds may contain small leaks, in which case oil or water may not show up on the low pressure side for several days or perhaps weeks. Sometimes the inner weld is made intermittent or holes are drilled in the inner lap to apply the full pressure to the outer weld so that leaks may be found at once. Sometimes a pressure is applied between the welds by drilling and tapping one weld. Air or gas pressure will usually reveal a leak at once. When the test is made with air or gas pressure, leaks may be detected by immersing the suspected area in water, covering it with liquid soap or using some chemical indicator that will respond to the gas under pressure.

One of the best tests for tightness consists in observing the loss in pressure over a given time. If water or oil is used, and all air or gas eliminated from the vessel, the loss in pressure will be very rapid for a small leak. An ordinary pressure gage is satisfactory to indicate the pressure loss. It frequently happens that it is not convenient to use oil or water either because the structure will not bear the weight, or because it is difficult to entirely remove the liquid after the test or for some other reason. Further, as pointed out above, a gas may be used to reveal leaks that would not be found with a liquid. When compressed gas or air is used, the drop in pressure is comparatively slow. The duration of the test must be increased or the pressure, temperature and barometric pressure measured with increased accuracy. A dead-weight tester can be used to determine the pressure more accurately. Small laboratory weights are used in addition to the standard weights supplied with the instrument so as to secure an exact balance. Uncertainty in measuring the average temperature of the gas in the line may introduce an error somewhat greater than that encountered in measuring the pressure, but the sections of line can usually be accepted or rejected on the basis of readings taken one to three days apart.

Destructive Testing

Destructive testing, that is testing to failure, gives a numerical measure of the properties under consideration. For example, if two welding procedures are being compared and both comply with the minimum requirements as shown by a proof test, a test to destruction may show that one is much superior to the other, and is to be preferred. Tests of standard laboratory specimens are usually carried to failure for this reason.

Destructive testing sometimes reveals defects that might not have been discovered in a proof test, but are objectionable as stress raisers or notches.

The obvious disadvantage of testing the entire weldment to destruction arises from the fact that the test can be applied to only a fraction of the number of weldments produced and the quality of the ones to be used must be inferred from the data relating to those destroyed.

In any sampling procedure, there is always the possibility that the sample may be better or worse than the lot from which

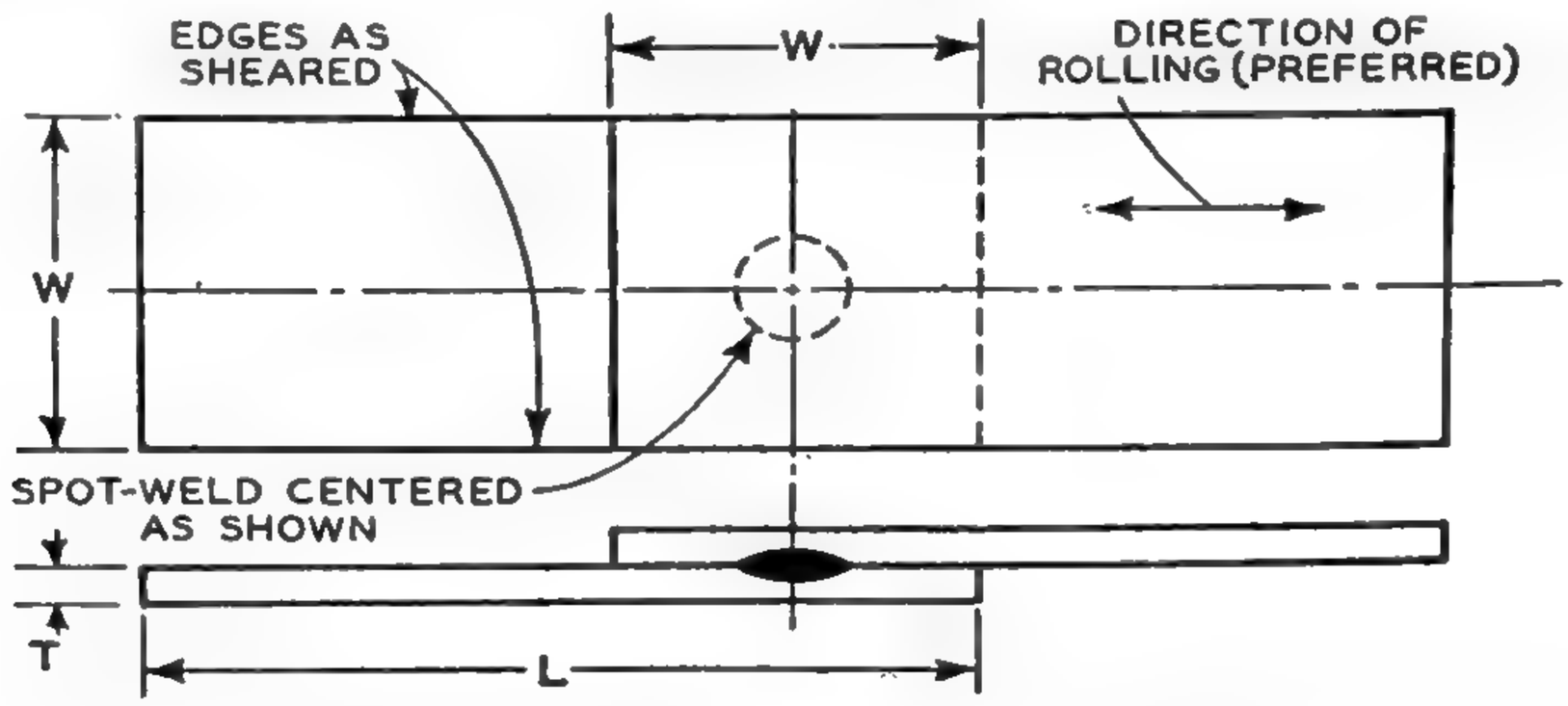
it is taken. This might result in accepting some lots that were below standard and rejecting others that were acceptable. However, there are some products which, by their nature, can only be evaluated by destructive tests and in such cases a sampling procedure must be adopted. Proper weight must be given to the penalty for an incorrect decision. If considerable damage might result from accepting a lot that should be rejected, a large sample and high standard of acceptance are required, while if little damage may be expected and stricter production controls are used smaller samples may be taken. Where the unit product cost is low and the parts are fairly small, destructive testing of samples selected from production lots may be more economical and may be more revealing than nondestructive examination. (See Chapter 44 for information on statistical control of weld quality.)

Resistance welded parts are frequently tested by selection of production parts which are tested to destruction. The testing procedure must be adapted to the particular work. Frequently strength tests can be made on the finished articles. At other times bend or deformation tests will reveal defects. The etch test can be used in almost all cases to reveal lack of soundness and Rockwell or similar tests for determining hardness.

For spot welding of sheet metal, the tension-shear test specimen shown in Fig. 51 or the peel test specimen shown in Fig. 52 may be used. In either case two metal strips of the kind and thickness used in production are welded under production conditions and tested to destruction. The tension-shear test will reveal the strength of the weld, the peel test will enable visual examination of the weld for soundness. A similar test for seam welds is the pillow test for which the specimen is shown in Fig. 53.

When standard test specimens may be prepared from a weld test specimen, or from a part taken from regular production, the *Standard Methods for Mechanical Testing of Welds* of the American Welding Society presents the accepted testing methods for many of the codes. Even when not mandatory, it represents good practice.

Sometimes a certain small percentage of welded parts is selected from a lot for destructive testing. Usually, the destructive force is applied so as to simulate service conditions. Vessels or tubing in-



T THICKNESS OF THINNER SHEET, INCHES AND U.S.S. GAGE	W SPECIMEN WIDTH, INCHES	L RECOMMENDED LENGTH, INCHES
UP TO 0.029 INCL. UP TO 23 GAGE INCL.	5/8	3
0.030 TO 0.058 INCL. 22 TO 17 GAGE INCL.	1	4
0.059 TO 0.115 INCL. 16 TO 12 GAGE INCL.	1 1/2	5
0.116 TO 0.190 INCL. 11 TO 7 GAGE INCL.	2	6
0.191 AND OVER 6 GAGE AND OVER	3	8

Fig. 51.—Tension-Shear Test Specimen

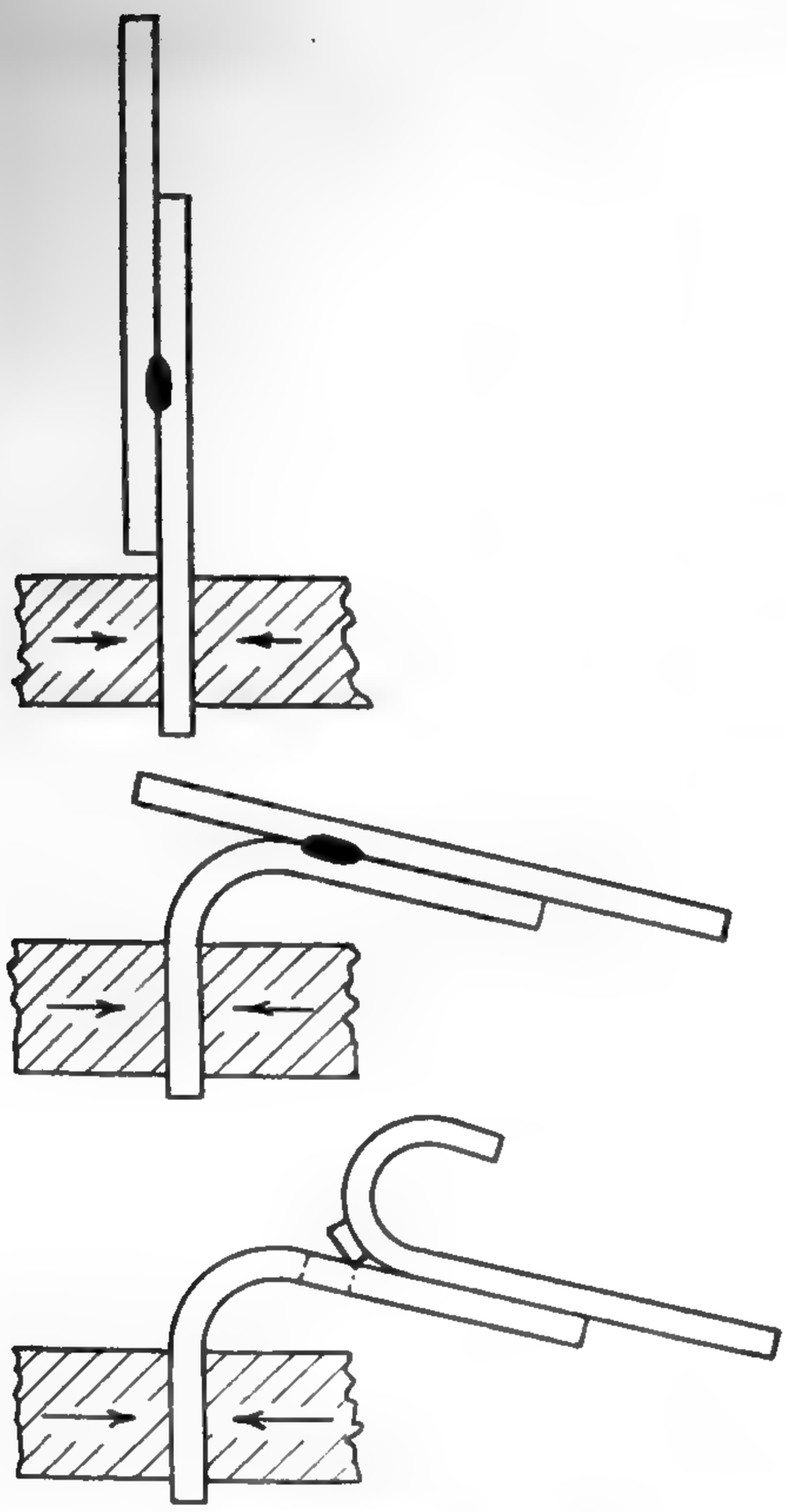


Fig. 52.—Peel Test

Step 1, Grip in vise or other suitable device. Step 2, Bend specimen. Step 3, Peel pieces apart with pincers or other suitable tool.

tended to resist internal pressure are tested to destruction with hydrostatic pressure. All air is usually allowed to escape from all high points because the energy stored in compressed air (if trapped during the test) might result in a destructive explosion. If objects are tested with air or any other gas under high pressure, a disruptive explosion may result and adequate safeguards should be employed. Usually 15 psi. is considered the maximum safe air or gas pressure to be used in a small or medium-sized vessel without guards around the vessel, but a large tank failing at 15 psi. may do considerable damage unless precautions are taken to avoid personal injury or property damage.

The number of specimens selected for destructive test should be given careful study. Applying the principles of *sequential sampling* will usually result in a saving. A small sample is tested and if they are all excellent, the lot may be accepted. If all fail, the lot may be rejected. If the performance is near the border line of acceptability, a second larger sample is tested, and this procedure continued until there is enough evidence to justify acceptance or rejection.

OTHER INSPECTION METHODS

Sampling by Trepanning and Similar Methods

In the trepanning method of sampling a small ring-shaped sample is removed with a hole saw or trepanning tool, or a boat-shaped specimen removed with a special machine using a hemispherical saw. The trepanned specimen is used for etch tests. The boat-shaped specimen may be used to make impact tests, miniature tension tests or etch tests. While it is usually necessary to repair the opening by welding, this procedure is classed as a non-destructive test.

The principal advantages of this method are that relatively inexpensive equipment is required, it can be performed without special training, the overall cost is moder-

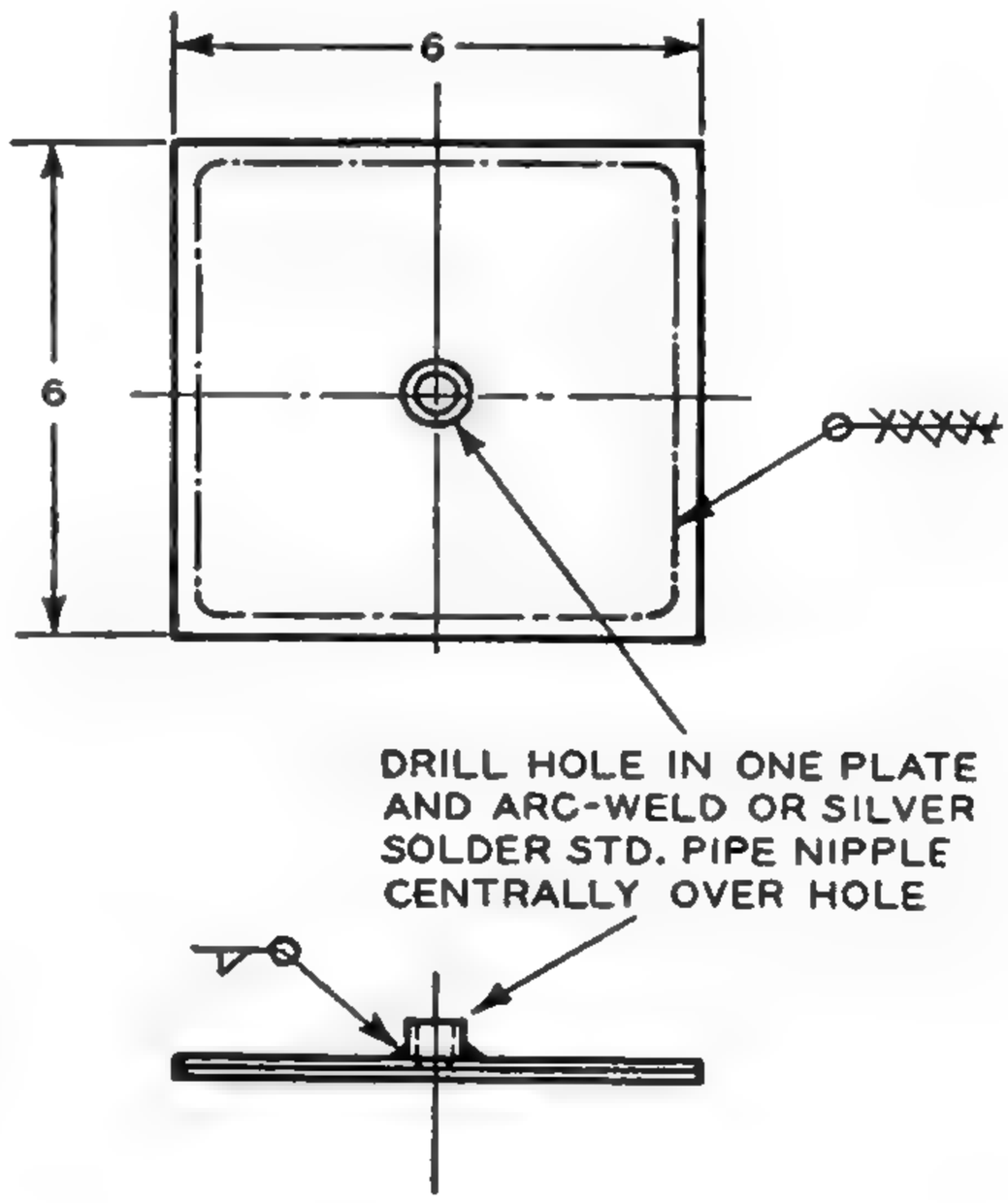


Fig. 53.—Pillow Test Specimen

ate and a definite spot check on the soundness of welds is assured. Like all spot checking or sampling methods it is useful in controlling the probable average quality, rather than in screening out defective work after the job is finished.

Sectioning as a method of inspection is accepted by several of the leading codes, including the AWS *Standard Rules for Field Welding of Steel Storage Tanks,* the AWWA *Standard Specifications for Elevated Steel Water Tanks, Standpipes and Reservoirs,* the API *Specifications for All-Welded Oil Storage Tanks* and the ASME *Code for Unfired Pressure Vessels.* These publications designate the number and size of specimens, the soundness required for acceptance and the methods of repairing the cut.

Sectioning provides an excellent and relatively inexpensive method of quality control in welding.

Use of the Stethoscope

Some years ago, the stethoscope was used in searching for defects in welds. The instrument was placed on the plate near the weld to be investigated and the work tapped lightly with a hammer. A cracked weld gives out a sound that is easily recognized. There is a good deal of difference of opinion as to the ability of the average inspector to detect borderline porosity or poor fusion. The method is not generally included in recognized codes at the present time.

Supersonic Testing

In this method a wave of the same nature as a sound wave but of a higher pitch is propagated in the metal object. The wave is reflected, at least partially, by any void or discontinuity. Frequently a cathode-ray oscilloscope is used to analyze the phase relation of the propagated and reflected waves. The distance from the surface to the defect can be measured on the screen.

This apparatus will show a defect in a large forging, lamination in a plate or variations in plate thickness. Its use to detect borderline porosity and inadequate fusion in welds is still under development.

BIBLIOGRAPHY

1. *Inspection and Testing of Welds,* R. B. Lincoln and N. Kraus, International Correspondence School, 1938.
2. *Visual Inspection of Welds,* J. F. Gibson, The Welding Journal, March 1938.
3. *Metallurgical and Industrial Radiology,* K. S. Low, The Pitman Publishing Co., 1940.
4. *Weld Inspection by Means of Trepanned Plugs,* W. T. Tiffin, The Welding Journal Res. Suppl., January 1940.
5. *Slide Carriage and Base Ring Weldments,* Navy Department, Bureau of Ordnance O.S. #1188.
6. *Magnaflux Aircraft Inspection Manual,* F. B. Doane and W. E. Thomas, Magnaflux Corp., Second Edition, 1941.
7. *The Radiographic Examination of Heavy Plate,* O. R. Carpenter, The Welding Journal, October 1941.
8. *Method of Testing Spot Welds,* R. E. Bowman, The Welding Journal Res. Suppl., October 1941.
9. *Principles of Magnaflux Inspection,* F. B. Doane, Magnaflux Corp., Second Edition, 1942.
10. *A Manual on Industrial Radiography with Radium,* Canadian Radium and Uranium Corp., 1942.
11. *Standard Methods for Mechanical Testing of Welds,* American Welding Society, 1942.
12. *Magnetic Powder Inspection of Weldments, Procedure to Be Used,* WXS-158, Army Specification, February 17, 1942.
13. *Certification Procedure for the Certification of Magnetic Inspection Operators,* Inspectors and supervisors, #20027-A, Army Air Force Specification, November 3, 1942.
14. *Methods of Chemical Analysis of Metals,* American Society for Testing Materials, 1943.
15. *Radiographic Inspection of Metals,* Otto Zamaskal, Harper & Bros., 1943.
16. *Industrial Radiology,* A. St. John and H. R. Isenburger, John Wiley & Sons, Second Edition, 1943.
17. *The Magnetic Power Method of Inspecting Weldments and Castings for Subsurface Defects,* C. H. Hastings, The Welding Journal Res. Suppl., January 1943.
18. *Fluorescent Method Detects Leaks in Process Vessels,* Frank Catlin, Chemical and Metallurgical Engineering, August 1943.
19. *Applicable Methods of Inspection for Pressure Vessels and Piping,* W. D. Halsey, The Welding Journal Res. Suppl., October 1943.
20. *Welding Instructions for Use by Welding Supervisors, Leaderman, Etc., of All Craft Concerned with Shipyard Welding,* U. S. Maritime Commission, The Welding Journal, December 1943. (Also available in bulletin form.)
21. *Tentative Method of Magnetic Particle Testing and Inspection of Heavy Forgings* (Serial Designation: A275-44T) American Society for Testing Materials.
22. *Tentative Method of Magnetic Particle Testing and Inspection of Commercial Steel Castings* (Serial Designation: A272-44T), American Society for Testing Materials.
23. *Production Spot Weld Testing,* J. H. Newsom, The Welding Journal, February 1944.
24. *Test Plugs Cut from Welds,* R. V. Anderson, Metal Progress, April 1944.
25. *Radiography Applied to Welding,* L. W. Hall, Iron Age, May 25, 1944.
26. *Coast Guard Inspection of Welding in Shipbuilding,* R. D. Schmidtman, The Welding Journal, June 1944.
27. *Routine Inspection and Salvage of Machinery Weldments,* J. W. Owens, The Welding Journal, October 1944.
28. *Radiography for Development and Control of Aluminum Alloy Spot Welding,* G. W. Scott, The Welding Journal, November 1944.

29. *Magnetic Inspection of Aircraft Parts,* No. A-260-2, Army Specification ATSC Technical Directive, November 21, 1944.

30. *Inspection Handbook for Manual Metal Arc Welding,* American Welding Society, 1945 (also available U. S. Army Ordnance Dept. M-608-2).

31. *Symposium on Magnetic Particle Testing,* American Society for Testing Materials, 1945.

32. *Determining Soundness of Welds in Line Construction; Magnaflux Method,* W. F. Cranshaw and D. E. Abbey, Petroleum Engineer, March 1945.

33. *Recommended Rules for Repairs by Fusion Welding of Power Boilers,* National Board of Boiler and Pressure Vessel Inspectors, September 13, 1945.

34. *Magnetic Particle Inspection Manual,* General Motors Standards, Vol. II, September 1945.

35 *Examination of Welded Joints by Trepanning with Special Application to Shipbuilding,* J. A. Arthur and H. N. MacKusick, The Welding Journal, October 1945.

36. *Recommended Practices for Resistance Welding,* American Welding Society, 1950.

37. *Aeronautical Material Specifications, Magnetic Inspection* (AMS-2640B), Society of Automotive Engineers, April 1946.

38. *Some Results of Advances in Welding and Radiography on the Welding of Pressure Vessels,* O. R. Carpenter, The Welding Journal, June 1946.

39. *The Radiography of Spot Welds in Light Alloy and Ferrous Sheet Material,* R. C. McMaster and F. C. Lindvall, The Welding Journal, September 1946.

40. *Fluorescent Penetrant Method of Inspection,* AN-1-30A, Army-Navy Aeronautical Specification, September 1946.

41. *Black Light for Weld Inspection,* Sanford Markey, Modern Machine Shop, October 1946.

42. *Magnetic Particle Inspection Process,* Army-Navy Aeronautical Specification, AN-1-39, October 21, 1946.

43. *Radiography in Modern Industry,* Eastman Kodak Co., X-Ray Div., 1947.

44. *Transcript of Conference on Weld Inspection with Magnaflux,* Magnaflux Corp., May 1947.

45. *Magnetic Particle Inspection of Weldments,* S. L. Henry, Metals Progress, July 1947.

46. *The Inspection and Testing of Brazed Joints with Especial Reference to Silver Alloy Brazing,* J. L. Christie and A. M. Setapen, The Welding Journal, September 1947.

47. *Radiology of Joints in Welded Piping for Power Plants,* H. Thomas, Mechanical Engineering, June 1948.

48. *Testing of Welds with Supersonic Waves,* B. Carlin, The Welding Journal, June 1948.

49. *The Value of Scientific Inspection to Industry,* William Hitt, Western Machinery and Steel World, July 1948.

CHAPTER 43

THERMAL AND MECHANICAL TREATMENTS OF WELDMENTS*

INTRODUCTION

THE EXPANDING application of welding in engineering structures and its use in fabricating the many types of alloys needed by modern industry have increased the number and complexity of treatments used to insure satisfactory weldments. The rapid growth of welding has not been fully matched by increase in knowledge and understanding of possible thermal and mechanical treatments of weldments, and of their benefits and limitations. Fortunately, the majority of weldments are structures which do not require any treatment. Unfortunately, the transition to the need of some treatment is often not definite or well marked, and so the treatments used for many weldments are a result of trial and error. This in turn often poses the alternatives of subjecting a weldment to an unnecessary and expensive treatment or running a risk of losing it during fabrication, or worse still of having it fail in service.

Various construction codes as well as insurance companies and purchasers' specifications generally set up minimum treatment requirements where safety is a consideration. It should be remembered and be impressed on the minds of cost-conscious fabricating personnel that usually these requirements are the minimum compatible with safety and that the fabricator has a responsibility to meet them fully or even exceed them. On the other hand, some of the code requirements are based on an improper understanding of the phenomena involved and the requirements imposed are of doubtful benefit. The safest and, in the long run, the best policy for the design and fabrication of weldments is not to rely blindly on code requirements and on the present imperfect knowledge of the subject but to attempt as much as economically possible to find out by adequate tests and experiments the need and benefits of treatments for the specific weldments in question.

In general, this chapter attempts to cover only treatments applied to the welded joint or found necessary because of the weld. For example, the shot peening of a flash-welded shaft in an area remote from the joint to increase its fatigue resistance in cyclic operation is not considered since such treatment, used to produce desired properties in non-welded structures, is generally well covered in works classified under their respective arts and sciences. Also, the complexity of the questions that may arise in the treatment of weldments prohibits the inclusion in this chapter of other than the fundamentals involved, together with specific information on the more important or widely used thermal and mechanical treatments. Chapter 3, Fundamentals of Welding Metallurgy, provides the necessary information relative to the metallurgical theory involved in the various thermal treatments covered by this chapter.

Just as a language is necessary to communicate thought, so is a common use of terms necessary to discuss methods of treating weldments. The correct use of accepted terms can do much to avoid errors. The definitions given below, except the parts enclosed in brackets, are taken from the ASM *Metals Handbook*, 1948. Other terms used herein conform to the standard terminology of the Ameri-

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can Welding Society as shown in Chapter 1.

Glossary of Terms (Especially as Related to Ferrous Alloys)

Aging.—In a metal or alloy, a change in properties that generally occurs slowly at atmospheric temperature and more rapidly at higher temperatures.

Annealing.—A process involving heating and cooling, usually applied to induce softening. The term also refers to treatment intended to alter mechanical or physical properties, produce a definite microstructure, or to remove gases. . . When applied to ferrous alloys, the term annealing, without qualification, implies full annealing. Any process of annealing will usually reduce stresses, but if the treatment is applied for the sole purpose of such relief it should be designated as *stress relief.*

Full Annealing.—A softening process in which a ferrous alloy is heated to a temperature above the transformation range and, after being held for a sufficient time at this temperature, is cooled slowly to a temperature below the transformation range. The alloy is ordinarily allowed to cool slowly in the furnace, although it may be removed and cooled in some medium that insures a slow rate of cooling.

Homogenizing.—A process of heat treatment at high temperature intended to eliminate or decrease chemical segregation by diffusion.

Modulus of Elasticity.—The slope of the elastic portion of the stress-strain curve in mechanical testing. The stress is divided by the unit elongation. The tensile or compressive elastic modulus is called *Young's modulus;* the torsional elastic modulus is known as the *shear modulus* or *modulus of rigidity.*

Normalizing.—A process in which a ferrous alloy is heated to a suitable temperature above the transformation range and is subsequently cooled in still air at room temperature.

Precipitation Hardening.—A process of hardening an alloy in which a constituent precipitates from a supersaturated solid solution.

Quenching.—A process of rapid cooling from an elevated temperature by contact with liquids, gases or solids.

Solution Heat Treatment.—A process in which an alloy is heated to a suitable temperature, is held at this temperature long enough to allow a certain constituent to enter into solid solution and is then cooled rapidly to hold the constituent in solution. The metal is left in a supersaturated, unstable state and may subsequently exhibit age hardening.

Stabilizing Anneal.—A treatment applied to austenitic stainless steels that contain titanium or columbium. This treatment consists of heating to a temperature below that of a full anneal in order to precipitate the maximum amount of carbon as titanium carbide or columbium carbide. This eliminates precipitation at lower temperatures which might reduce the resistance of the steel to corrosion.

Stabilizing Treatment.—A thermal treatment designed to precipitate material from solid solution, in order to improve the workability, to decrease the tendency of certain alloys to age harden at room temperature, or to obtain dimensional stability under service at slightly elevated temperatures.

Strain.—Deformation [resulting from stress] expressed as a pure number or ratio. [In uniaxial tension the change in length divided by original length.]

Stress.—The load per unit of area. Ordinarily stress-strain curves do not show the true stress (load divided by area at that moment) but a fictitious value obtained by using always the original area.

Tempering (Drawing).—A process of reheating quench-hardened or normalized steel to a temperature below the transformation range, and then cooling at any rate desired.

Tensile Strength.—The value obtained by dividing the maximum load observed during tensile straining by the specimen cross-sectional area before straining. Also called *ultimate strength.*

Yield Strength.—The stress at which a material exhibits a specified limiting deviation from proportionality of stress to strain. An offset of 0.2% is used for many metals such as aluminum-base and magnesium-base alloys, while 0.5% total elongation under load is frequently used for copper alloys.

Yield Point.—In mild or medium-carbon steel, the stress at which a marked increase in deformation occurs without

increase in load. In other steels and in nonferrous metals this phenomenon is not observed.

REASONS FOR THERMAL AND MECHANICAL TREATMENTS OF WELDMENTS

General

The basic purpose of welding is to join permanently a number of component parts into a single unit. The basic requirement of welding is to produce a joint which will enable full utilization of the properties of the component parts in service. This means first of all that the weld itself must be sufficiently strong to permit the component parts to carry the maximum loads they are required to carry. It also means that the component parts must not be weakened by the weld in any way which would decrease their original load-carrying capacity. A weakening may be produced in a number of ways, such as reduction of the original cross-section (undercutting); introduction of a sharp concentration of stress, as would occur at an excessively heavy fillet weld or at a heavy butt weld reinforcement; or a change in the structural or corrosion-resistant properties, which frequently occurs in the zones of the component parts affected by the heat of welding.

A secondary requirement of welding is to produce a joint capable of successfully undergoing whatever additional fabricating operations may be necessary. Thus, a welded joint must be machinable, and it must be dimensionally stable during machining.

As explained elsewhere in this HANDBOOK, adherence to proper welding techniques and procedures will produce welds which will satisfy requirements in all cases. Under certain conditions however, satisfactory weldments cannot be produced without including some form of preweld or postweld treatment, which may be thermal or mechanical, in the welding procedure.

In general it can be said therefore that the basic purpose of thermal or mechanical treatment of weldments is to improve their performance either during fabrication or in subsequent service, above and beyond that which can be accomplished with proper operational skill, methods and joint designs.

The improvement of performance during fabrication consists of reduction and control of distortion during welding, improvement of dimensional stability during machining and improvement of machinability.

The improvements in service properties by thermal or mechanical treatment consist in the reduction of the notch effect produced by abrupt changes in hardness or other metallurgical discontinuities in or around the weld, complete or partial restoration of original structural and corrosion-resistant properties of component members in the heat-affected zone and possibly reduction of residual stresses in and around the weld. Occasionally improvement of the mechanical properties of the weld metal itself may also be obtained.

Improvement of Performance During Fabrication

Improvement of performance during fabrication actually begins with improvement in the factors affecting the ease of successful deposition of sound weld metal, that is weldability, of the joint. However the factors affecting weldability of different materials and joints are so interdependent that they are best treated together and for this reason thermal and mechanical treatments primarily intended to eliminate or reduce cracking of the weld metal or heat-affected zone are discussed further in Chapter 3 dealing with welding metallurgy and those chapters relating to specific metals. In general, preheating of the joints or of the entire structure to be welded is a common practice for reducing the tendency to cracking exhibited by some materials and weldments during or immediately after welding. The extent and degree of preheating varies from as low as room temperature (70°F. in case of welding outdoors in winter) to as high as 600°F. in case of some highly hardenable steels, depending on many closely allied factors such as hardenability of base and weld metal, their ductility as a function of temperature, rigidity and degree of restraint of the joint and many others.

In general the ensuing discussion deals with improvement of the performance of completed welded joints when subjected to such subsequent operations as forming, bending and machining. It also deals

with prevention and control of distortion produced by welding.

Control of Distortion.—Structural distortion in one form or another is incident to all forms of welding, and if improperly controlled may be sufficiently severe to render the weldment nearly useless. It is caused by two factors: the thermal contraction or shrinkage of the weld metal on cooling from molten to atmospheric temperature and the differential expansion and contraction of the metal adjacent to and affected by the heat of the weld.

The volumetric change in dimensions of carbon steel from its melting temperature to atmospheric temperature is approximately 6.8%, which means that a cube of molten metal would contract approximately 2.2%, in each of its three dimensions. However, in a welded joint the molten metal on solidifying becomes attached to the parts being joined and is therefore restrained by them from contracting freely in at least one and sometimes two dimensions. Since the volumetric dimension of any metal at any one temperature can vary only within its elastic limit and since the maximum elastic movement of steel is approximately only one-tenth of the total requisite thermal contraction, the weld metal will flow plastically and triaxially effecting most of the requisite volumetric contraction along the axis or axes of least resistance. In doing this it will exert considerable force on the parts being joined.

The degree of resistance of the parts to these forces will determine the degree of distortion of the structure and the extent of plastic flow in the weld metal. In general the greater the distortion and movement of the parts being joined, the smaller the plastic flow or strain in the weld metal and vice versa, the less distortion and movement of the parts the greater the strain in the weld metal. Excessive strain in the weld metal generally results in cracking at some point during the cooling cycle and thus the two opposite pitfalls of welding appear to be weld cracking and excessive distortion. The theoretical analysis of the shrinkage phenomenon is complicated by the fact that in metals undergoing phase transformation such as all ferritic steels, additional volumetric changes occur during transformation and that in all metals the properties such as coefficient of expansion, elastic limit, yield strength and modulus of elasticity are functions of the temperature (see Table 1).

In addition to the distortional forces exerted by the cooling weld metal on the parts being joined, the parts themselves will tend to become distorted as the result of localized heating produced by the welding operation. It must be remembered that in practically all forms of welding, temperature differences and gradients exist sufficiently severe to cause plastic flow in regions adjacent to the weld both on heating and cooling. Unfortunately, these volumetric changes are not equal and opposite on contraction and expansion, the heated portion tending to become upset, or shorter and thicker on heating and cooling than the relatively cool remainder of the weldment.

Figure 1 shows a very simple case of upsetting. Theoretically a temperature difference of less than 200°F. is necessary between *a* and *b* to cause plastic upsetting. In most forms of welding the

Table 1—Mechanical Properties of Mild Steel at Elevated Temperatures

Temp., °F.	Ultimate Strength, Psi.	Yield Point, Psi.	Elastic Limit, Psi.	Modulus of Elasticity, Psi.	Elongation in 2 in., %	Reduction of Area, %
100	54,000	39,000	36,000	30,700,000	48	68
200	56,000	43,000	33,000	29,000,000	43	66
300	58,000	46,000	28,000	27,300,000	39	65
400	60,000	47,000	22,000	25,600,000	37	64
500	63,000	46,000	16,000	23,900,000	37	64
600	66,000	44,000	14,000	22,200,000	40	66
700	60,000	40,000	12,000	20,500,000	44	68
800	52,000	37,000	10,000	18,000,000	49	76
900	43,000	32,000	8,000	17,100,000	55	84
1000	34,000	27,000	7,500	15,400,000	60	90
1100	25,000	21,000	5,000	13,700,000	64	94
1200	19,000	17,000	3,500	12,000,000	68	96
1300	14,000	13,000	2,000	10,300,000	72	98

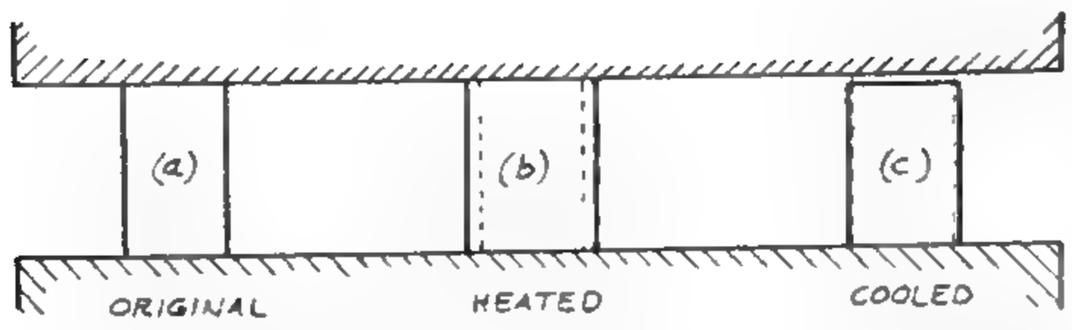


Fig. 1.—Dimensional Changes Due to Temperature Differential

Dotted lines show original size.

heat is applied sufficiently rapidly to produce, even under most favorable welding conditions, a temperature gradient sharp enough to produce considerable upsetting.

The important factors governing amount of upsetting and hence distortion are (*a*) the resistance of the structure to the free expansion of the weld volume; (*b*) the temperature gradient which in turn is determined by the rate at which heat is applied and the rate at which it is conducted away from its point of application; (*c*) the coefficient of expansion of the metal, which determines the total amount of plastic movement; and (*d*) the yield strengths of the base and weld metal, which limit the residual forces which can exist within the structure.

Distortion of a weldment is further aggravated by the fact that the geometry of most weld joints tends to cause an angular movement between the parts being joined as illustrated in Fig. 2.

From Fig. 2 (*b*) it can be seen that the geometry of cross-section of most common welds is responsible for some angular movement. Since the measurement at the root is very much shorter than at the top, the total shrinkage is much less. This difference in total shrinkage between top and bottom can only be observed by angular change.

Figure 2 (*c*) shows the mechanics of layer-by-layer deposit. Each successive layer must shrink pulling the plates about the previous deposit as a hinge.

In general three basic methods of minimizing distortion are widely used. One is to stretch the weld metal immediately after it is deposited, and preferably while it is still hot, by a series of hammer blows or peening. The second is to distribute and balance the forces and stresses produced by weld shrinkage and upsetting, by special welding techniques and sequences while the third is to forcibly restrain the parts being joined

Fig. 2.—Angular Distortion and Shrinkage

from distortion and movement during welding by means of suitable jigs and fixtures.

All three methods attempt to increase the plastic flow or strain of the weld metal on cooling and for this reason all are subject to the same limitation of cracking of the weld metal if carried too far.

Peening, since it actually aids plastic flow by application of external compressive forces normal to the plane of maximum tensile stress, can probably accomplish the most weld straining without cracking. Unfortunately the effective depth of a surface blow is quite shallow and peening is most effective in relatively thin weld beads not over $^3/_{16}$-in. thick.

Forcible restraint of the parts being welded, whenever possible, is the next most effective way of controlling and actually reducing distortion. It must be remembered however that, in general, the greater the restraint the greater the magnitude of stresses during welding, particularly the transverse stress, hence the greater the tendency to cracking.

Unfortunately many structures either because of their size or geometry, cannot be effectively restrained, and for many others the necessary jigs and fixtures are not economically practical.

The use of special welding sequences and procedures is usually the easiest and simplest method for controlling distortion and should always be tried before deciding on what additional steps may be necessary. In fact use of incorrect welding sequences may produce distortion severe enough to defy all methods of correction.

Again it must be remembered that a sequence or procedure intended to produce less distortion is not necessarily the one to produce less stress during welding but may on the contrary produce welding stresses severe enough to crack the weld or even fracture parts being joined. In fact, such sequences do not attempt so much to reduce stresses during welding as to distribute and balance them in such a manner as to produce less movement or distortion of the parts. As will be shown in the section on residual stresses, all welds over a certain minimum length develop longitudinal stresses up to the yield point of the weld or base metal used, which become locked up in the joint on its completion regardless of the sequence or procedure used. Transverse stress however, that is stress across the weld, can be frequently controlled by selection of proper welding sequence.

Dimensional Stability on Machining.—As explained in greater detail in the section on residual stresses, all welds and adjacent areas contain a system of locked-up tensile and compressive stresses balancing each other. Maintaining dimensional stability during and following machining is essentially a matter of controlling the stresses released by the unbalancing of the system of stresses which may occur on machining of a weldment. The most effective insurance against dimensional instability during machining is thermal stress relief.

Neither the necessity of a treatment to induce satisfactory stability in any particular weldment nor the degree of stability that will be attained by any given treatment in a particular weldment can easily be reduced to a formula. In addition to considering the degree of accuracy required in machining, there also must be considered the proximity of the machining to heavy welds; i.e., whether machining will remove weld metal or base metal containing part of the locked-up system of stresses. Also the length of any machined surface subject to rotational movement about the weld zone, is important. If many small units are involved, experimentation is generally superior to attempted logical prediction in determining the need for a treatment prior to machining. When a large single weldment is in question on which machining to close tolerances in the vicinity of heavy welds is required, it is safer and often less costly to stress relieve than to experiment.

The degree of stability obtained by a thermal stress relief has been shown to be a function of the maximum temperature and the time held at that temperature. In general short holding times at higher temperatures are much more effective in achieving machining stability than are longer times at lower temperatures. For example it has been demonstrated by Stitt that heating for 2 hr. at 1000°F. is more effective than 18 hr. at 900°F. in the reduction of movement during machining in several low-alloy and carbon steels and also that movement in a test piece stress relieved at 1300°F. for 2 hr. was approximately one-sixth of the movement of a

similar piece stress relieved at 1000°F. for the same length of time. Deflection following the 1300°F. treatment was approximately 5% of the deflection of the weldment machined in the as-welded condition.

Stresses which can affect the dimensional stability of weldments during machining may be introduced by the unequal cooling of various parts of a weldment, sometimes as a result of too rapid a cooling rate during stress relief. Another factor to be considered in the stability of weldments is the procedure followed in machining and the sequence of cuts made. If one side of a flat surface is finished prior to the rough machining of the opposite side, distortion will generally occur in the first surface machined. For extreme accuracy structures have been rough machined on all surfaces, then stress relieved to remove the cold worked surface resulting from this machining before making finishing cuts on any surface.

Improvement of Machinability.—Machinability may refer to tool life, the possible speed of a machining operation, the force or energy required in cutting, or the ease of obtaining a satisfactory finish. Many factors affect the machinability of a structure. Included among these are the composition, hardness, metallurgical structure and work-hardening characteristics of the material. Since both hardness and metallurgical structure are dependent upon composition and heat treatment, often much can be done to provide the machine shop with a weldment of improved machining qualities.

Little difficulty is ordinarily encountered in the machining of low-carbon steel, either as-welded or in the stress-relieved condition. Sometimes, however, a surface tearing or drag is noted in the cut over a weld surface. This tendency can be reduced to some extent by the selection of a welding procedure producing a deposit of somewhat greater hardness.

Since the machining qualities of a material generally deteriorate as the Brinell hardness increases beyond 210 to 250, special treatments are often necessary to improve the machining properties of higher carbon steels and alloys. Fortunately these treatments, such as preheating and postheating, are also desirable to avoid the possibility of cracking and to develop other serviceable properties.

The machining of a structure in which the cut must include a weld can become a serious problem if certain requirements, such as a high surface quality, are specified. It may be impossible to adjust the external variables under the control of the machinist, including cutting fluids, tool shape, feeds and speeds, to produce the desired surface if there is great variation in the properties of the weld, the plate and the heat-affected zone. For optimum machining the properties of the base metal should receive first consideration, and compromises which might result in increasing the difficulties of machining the base metal should be accepted reluctantly. One helpful solution is to redesign and eliminate welded joints in the surface to be finished, or to place welded joints in areas where finish is unimportant. Another solution is to fully anneal or normalize and temper the weldment (depending on the material involved) after selecting the weld deposit which will most nearly match the base material in hardness after heat treatment. These treatments tend to eliminate the extreme difference in grain structure and hardness present in the as-welded and stress relieved heat-affected zones.

Hardness of weld metal or base metal in some compositions can make machining impracticable. For the medium carbon and low-alloy groups of steels which do not have deep hardening properties, preheat and a high welding heat input through the use of large electrodes, and a slow rate of welding can be used to reduce the as-welded hardness by reducing the cooling rate of the weld and adjacent base metal. Materials of higher carbon content or with sufficient alloying constituents will harden excessively regardless of the preheat since they have a critical cooling rate far slower than is possible to attain by welding. A. Edson has presented a chart which can be used to predict approximately the maximum hardness that will be developed in the base metal from its chemical composition (see Bibliography).

Improvement of Performance in Service

As explained in other chapters of this HANDBOOK, proper design and preparation of the joint and selection of a proper welding procedure together with adequate operational skill will produce a sound

welded joint which to all outward appearances and for most service requirements cannot be distinguished from a homogeneous section such as would exist if the weldments were produced by the same process of casting, rolling or forging as its component parts. However, as explained in detail in Chapter 3, Fundamentals of Welding Metallurgy, this is not strictly true of any welded joint in the as-welded condition, as it definitely differs in several ways from a homogeneous section, though in most cases proper thermal treatment can usually reduce these differences to substantially zero. For certain service conditions the differences may be significant and it then becomes desirable to subject the weldments to a suitable thermal treatment.

As mentioned before, the differences between a completely homogeneous joint and a properly made welded joint consist of the different metallurgical structures of the component zones of the joint, and in the presence of a system of balanced stresses locked-up in the joint during welding. The significance of these differences and the common reasons for their removal are as follows.

Heat-Affected Zone.—In considering thermal effect of welding on the properties of the component parts, the first thing to remember is that different metals are affected in different manners by the heating cycle of the weld. All metals can be divided into three types depending on their response to the heat of welding as follows: Ferritic steels such as plain carbon steels which undergo phase changes when subjected to heating and cooling; austenitic steels such as 18–8 stainless and in general all metals which are usually hardened by cold work; and metals such as certain aluminum and magnesium alloys which are susceptible to solution and precipitation hardening. The effect of welding, as explained in Chapter 3, generally is a hardened zone of greater tensile strength and lower ductility in the first type and a softened zone of lower tensile strength and greater ductility in the second. The response of the third type is less uniform in many cases being similar to that of the second type, while in others decrease in tensile strength is not accompanied by increase in ductility.

It is easy to understand the desirability of a treatment which will restore the original tensile strength of the precipitation hardened metal, in the areas adjacent to a weld. Restoration of properties originally obtained by cold work and lost through the annealing effect of welding is also usually desired though less often attempted since mechanical working of a completed weldment is not as a rule practical except in the case of thin sheets where a degree of restoration can be obtained by peening or trip-hammering the heat-affected zone.

The significance of the hardened zone next to the weld is not fully understood. It may be harmful, of little consequence or beneficial, depending on its metallurgical structure and on the metallurgical structure of the rest of the joint. Practically all steels are notch-sensitive below a certain temperature or above a certain strain rate. The mechanism of behavior of a notch-sensitive steel under stress is not too well known, but in practice such a steel exhibits a reluctance to flow plastically and absorbs energy in the presence of a notch or any other structural or even metallurgical discontinuity or stress raiser. Furthermore, if such a steel fails under load locally at a point of high stress concentration the resultant failure or cracking will propagate at high rates of speed through adjoining members until the metallic continuity of the steel through which it travels is interrupted (as at a geometric opening in the structure) or until it reaches a region stressed in compression. Therefore structures operating at temperatures at which their constituent steels become notch sensitive, may fail at average stress levels well below normal design values provided stress concentrations capable of starting a local crack are present. Although the most severe stress concentrations are usually caused by poor design geometry, other factors, such as weld cracks or abrupt changes in metallurgical properties have been known to produce a dangerous stress concentration capable of starting a failure under certain conditions of load and temperature.

The temperature at which a steel becomes notch sensitive varies greatly with its composition, its thickness and the rigidity of the structure which it forms. For instance austenitic chromium-nickel steels are notch-tough in all types of structures and in all thicknesses at temperatures as low as that of liquid air.

On the other hand, many carbon-steel plates and shapes are notch sensitive at

temperatures as high as +100°F. and almost all are notch sensitive below +20°F.

The phenomenon of notch-sensitivity appears to be allied to the general toughness of steel or its ability to withstand impact or shock loading. Thus, steels having high transition temperatures will generally shatter at comparatively low shock loading while steels having high shock resistance invariably have extremely low transition temperatures. Perhaps a better way to describe the difference between tough and notch-sensitive steels is that in tough steel failure always is preceded by considerable plastic deformation and is therefore confined to highly strained sections, whereas in notch-sensitive steel fracture may take place with little preceding plastic deformation, or having started at an area of considerable plastic deformation progresses through plastically unstrained sections.

This phenomenon has received much attention in the last few years and considerable recent literature on this subject is available.

It appears reasonably certain that the steep hardness gradient commonly found in the heat-affected zone of most ferritic steels acts similarly to a notch and for this reason its elimination or reduction is desirable.

In notch-tough steels, such as many low-alloy steels, the presence of a hardened zone is of less importance, since decreased ductility of the heat-affected zone is usually accompanied by increased yield and ultimate strengths which means that in case of stress transverse to the axis of a weld the softer material on each side of the hardened zone will deform and flow plastically before the zone is stressed beyond its yield point. There are of course, exceptional cases, particularly during fabrication, where as a result of subsequent fabricating operations the heat-affected zone of a welded joint may have to undergo appreciable deformation. For instance an alloy steel pressure vessel subjected to an internal pressure overload will usually expand and deform around the hardened areas adjacent to the welds without failure of the welds. However, if two butt-welded plates have to undergo severe bending along a line normal to the line of weld, the weld may fracture in the heat-affected zone due to its lower ductility.

In addition to the hardened zone, many alloy steels, particularly those of the quench-and-draw type, develop a soft zone which, although usually quite ductile in the conventional sense of the word, may be relatively notch sensitive and may cause failure under certain conditions of temperature or high rate of loading even though the magnitude of the fracturing load is comparatively low. Short of requenching and redrawing the completed weldment, which is only practical for the most simple type of structure, little can be done after welding to improve the original properties of such softened zones. However, softening can be kept to a minimum by sharply limiting the rate of heat input into the weld, thus insuring rapid cooling.

Recent investigations have established that all arc-welding electrodes having so-called cellulose-type coverings (e.g., E6010, E6011), used for welding mild and low-alloy steels, saturate the weld and the heat-affected zone with hydrogen. It has been also established that on medium and deep hardening steels this hydrogen saturation is at least partially responsible for underbead cracking during welding and as a result electrodes suitable for welding mild and low-alloy steel are now available with a lime or low hydrogen type covering (e.g., E6015 and E6016).

There is also enough experimental evidence to justify a theory that hydrogen in the weld metal and the heat-affected zone increases notch sensitivity and that therefore any thermal treatment which tends to drive hydrogen out of the welded joint increases the notch toughness of the joint. Thermal stress relief at 1200°F. is very effective in driving out most of the hydrogen from the welded joint and this fact appears to be a further reason for subjecting weldments to thermal stress relief when they are intended for service demanding highest possible notch toughness.

There is some evidence that low-hydrogen electrodes, without preheat, produce joints which are nearly as notch tough as thermally stress-relieved joints made with cellulose-type covered electrodes, and that with 300 to 400°F. preheat they produce joints superior to the thermally stress-relieved joints.

As explained in detail in Chapter 31A all austenitic chromium-nickel steels containing more than 0.02% carbon become

susceptible to intergranular corrosion in the heat-affected zone after welding unless stabilized with columbium or titanium. The susceptibility of unstabilized stainless steels to corrosion is in direct proportion to the carbon content and to the length of time the zone remains within a temperature range of 800 to 1800°F. during welding. However, for most commercial grades of stainless steel, in thin sections ($^1/_2$ in. and less) the decrease in corrosion resistance produced by arc welding is slight and seldom warrants a subsequent thermal treatment. In any case the completed weldments should be thermally treated where the highest degree of corrosion resistance is required; for plates more than $^1/_2$ in. thick; and for most gas-welding applications regardless of thickness. It is usually more economical to use low-carbon or stabilized steel than to employ such treatment which, to be effective, involves temperatures in excess of 1800°F. and very rapid water or air quench with resultant danger of warpage and distortion.

Weld Metal.—A sufficiently wide choice of welding electrodes is available generally to permit a close matching of the properties of most metals and alloys without subsequent thermal treatment. Accordingly, thermal treatment of weldments intended primarily to improve the structural properties of the weld metal are not common. A notable exception exists in the case of precipitation-hardenable alloys where the deposited metal as well as the heat-affected zone are usually considerably weaker than the hardened alloys and where it is usually necessary to resort to some form of thermal treatment to improve the properties of both.

In many cases involving highly ductile metals, the ductility of the weld metal although adequate for most service requirements, cannot quite match the ductility of the base metal without subsequent thermal treatment. Accordingly, whenever highest ductility of weld metal is desired the weldment is usually subjected to a thermal treatment. The subcritical thermal stress relief normally reduces the yield and tensile strengths of mild steel weld metal while it increases ductility. In general the higher the stress-relieving temperature the greater the increase in ductility.

Some ferritic low-alloy weld metals containing nickel, copper and molybdenum or vanadium and molybdenum will show a decrease in ductility from the as-welded condition if stress-relieved in the temperature range where precipitation-hardening or aging takes place. One disadvantage of this phenomenon is that such a precipitation-hardening weld deposit is sometimes inadvertently obtained through dilution of weld with plate material and consequently the heat treatment which is intended to increase ductility actually decreases it. Another oddity of similar nature is a decrease in ductility which has been observed in some welds low in chromium and molybdenum when stress-relieved in the 1100 to 1250°F. range.

Locked-Up Stresses.—In the section on control of distortion it was mentioned that triaxial plastic flow or plastic strain occurs during welding in and around every weld as the result of stresses induced by unequal expansion and contraction of the weld metal, the heat-affected zone and the unaffected base metal. The plastic strain in and around the weld produces an elastic strain of the opposite sign in the metal which has remained relatively cool during welding and is resisting the contraction of the cooling metal of the weld. That is, in causing the heated metal to stretch during cooling, the weldment as a whole is compressed. These opposing strains produce a system of stresses locked up in the weldment and mathematically balancing each other.

The theoretical determination of the residual stresses is extremely difficult if not impossible but residual (relaxed) strain can be relatively easily measured by suitable strain gages, after mechanically severing the areas of opposite strain. By judicious use of this severing or mechanical relaxation technique the magnitude and pattern of residual strains in the entire weldment can be determined. Locked-up stresses can then be readily calculated. A great many such determinations have been made within the last few years on a great variety of weldments, as a result of which a reasonably clear and accurate picture of residual stresses in weldments now exists.

In general it may be stated that residual tension of yield-point magnitude exists in the longitudinal direction in all welds over 18 in. in length, balanced by wide bands of relatively low residual compression on each side of the weld as shown on Fig. 3. Proportionately lower residual stresses

exist in shorter welds unless conditions of unusual longitudinal restraint are present. Normally residual stresses of much lower magnitude exist across the weld or in the transverse direction. In the case of two wide plates progressively butt welded together without external restraint they usually consist of low tension of a few thousand psi. across most of the weld, balanced by two areas of compression, one at each end of the weld.

By introducing varying degrees of transverse restraint it is of course possible to increase transverse tension to any value up to the yield point of either the weld or base metal whichever is the lower. To be effective, restraint capable of raising transverse stresses appreciably must be applied within a few inches of the weld and under conditions of such high restraint, weld cracking usually effectively inhibits welding.

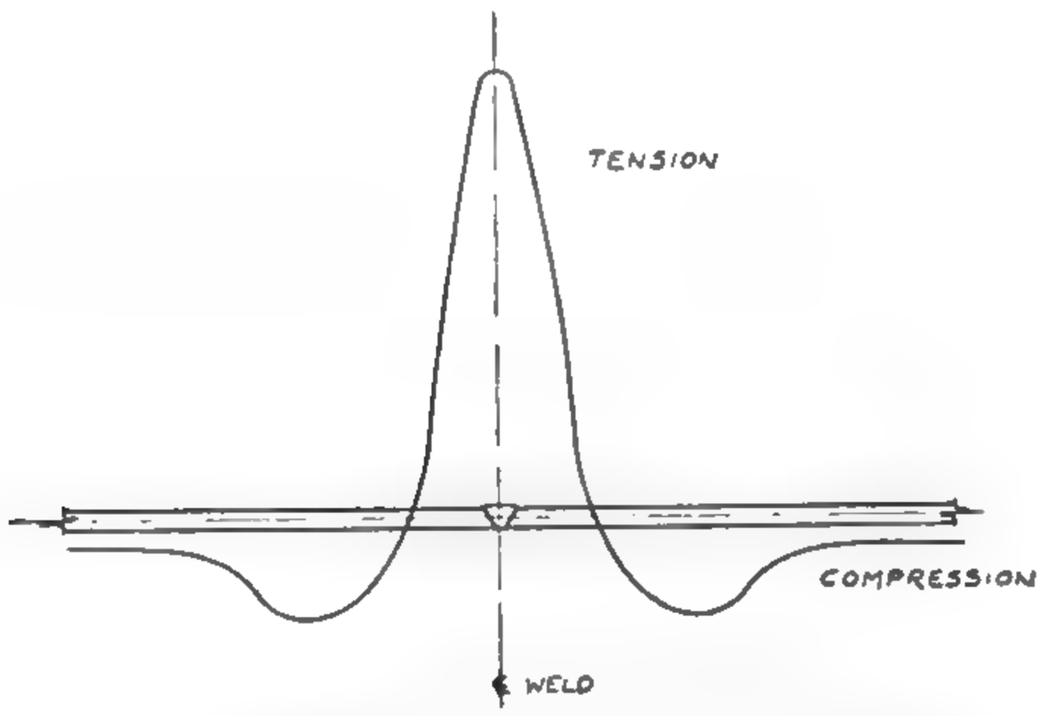


Fig. 3.—Distribution of Longitudinal Stresses

Basically residual stresses produced by welding are closely analogous to the systems of locked-up stresses present in most rolled sections such as I-beams and channels, in most castings and forgings and in many machined parts. Although little attention is generally paid to locked-up stresses present in such homogeneous sections considerable difference of opinion exists regarding their effect on the service performance of a welded joint or weldment. It can be and has been demonstrated that the over-all load-carrying capacity of a structural member or of an assembly of members is not affected by the presence of a system of balanced stresses within such members or assemblies whenever the load is applied at a comparatively low rate and in a manner to produce simple tension or shear stress. Considerable experimentation has been conducted in recent years to determine conclusively whether a balanced system of residual stresses affects service performance of a welded structure when subjected to more complex types of loading, such as dynamic loading, shock loading, loads producing high rates of strain and loads producing multi-axial stresses within and around the joint. None of these experiments have yet been able to establish any kind of relationship between residual stresses and service performance. It is interesting to note that these experiments did establish an improvement in performance of welded structures made from notch sensitive steels as a result of thermal treatment and that this improvement can be explained by changes in the metallurgical structures of the joint, principally reduction of the hardness level and gradient in the heat-affected zone. For instance in one set of experiments greater improvement in performance was achieved by a preheat treatment than by a conventional postheat or stress-relief treatment despite the fact that preheating did not diminish or otherwise affect the residual stresses in the weld or in the weldments, whereas the conventional 1200°F. stress-relief reduced the locked-up stresses to virtually zero.

The argument about the need for stress relief to improve service performance of weldments is to some extent academic, as in most cases where it is advocated as means of insuring the highest quality joint, thermal treatment should be used anyway to improve the metallurgical properties of the joint and to reduce its notch sensitivity.

It may be safely stated that best evidence to date indicates that residual stresses, per se, do not affect the service performance of welded structures under conditions of service investigated. Nevertheless, it must be remembered that no clear experimental proof exists that locked-up stresses do not adversely affect the performance of welded structures under any condition of service, primarily because it is virtually impossible to reproduce experimentally all conditions of service under which welded structures operate.

Code Requirements.—At present a number of regulatory bodies, such as the ASME Boiler Code Committee, specify a thermal stress relief for certain types of weldments. There is little doubt

that in a majority of cases this is a desirable practice since evidence exists to demonstrate improved performance of structures so treated over structures in the as-welded condition. It is well, however, to bear in mind that the best evidence to date indicates that this improvement is due to the changes in the metallurgy of the welded joint produced by the thermal treatment. Where it cannot be demonstrated that the metallurgy of the welded joint is improved by a stress-relief treatment, as for instance in case of weldments made of austenitic chromium-nickel steels, or of certain quenched and tempered low-alloy steels, the desirability of such a treatment is doubtful.

The various code requirements now in force are summarized in Table 2.

COMMON THERMAL TREATMENTS FOR WELDMENTS

Preheat

Preheating is beneficial and frequently mandatory in the gas welding of all heavy ($^1/_2$-in. and above) sections for most metals, in the welding of high thermal conductivity metals and in thermit welding to assure fusion between the filler metal and base metal. In the shielded metal-arc welding of steel it is very effective in reducing the rate of cooling with resulting lower hardness and also a wider heat-affected zone. Actual tests have shown that in steel structures having plate thicknesses up to $^3/_4$ in., preheating at 400°F. may produce 9% greater strength than is obtained by a 1000°F. postheat even though preheating has very little effect upon the residual stresses.

Preheating can be accomplished in many ways. One of the oldest methods still in wide use is to construct a temporary brick furnace around the structure as a whole or in part, using a charcoal or coke fire or gas burners as a source of heat. The area to be welded is generally placed so that it can be exposed without uncovering the entire structure, and without exposing the welder to excessive heat from the furnace. With such a furnace it is often possible to postheat the weld area or the entire structure for stress relieving or drawing purposes.

Regular heat-treating or stress-relieving furnaces are often used to preheat entire structures, especially heavy forgings or castings for repair welds. When the piece to be welded is removed from the furnace, protection against rapid cooling should be provided with asbestos paper or blankets.

Plate fabricating shops often use natural or manufactured gas as a fuel for the preheating of weldments since it is clean and convenient. It is used in torch-type burners, premixing the gas with air, or using compressed air in the torch. For longitudinal joints in pressure vessels a $^1/_2$- to $1^1/_2$-in. diam. pipe is sometimes drilled at intervals with 1/16 to 3/32 in. holes along one axis. Air is mixed with gas to produce a cleaner hotter flame along the joint. Caution must always be observed to avoid excessive temperature differentials when locally preheating since high stresses can be developed, resulting in distortion and broken tack welds.

Acetylene and bottled petroleum gas have been used for preheating and stress relieving small diameter pipe joints in chromium-molybdenum steel. The heat can be applied with torches or with muffle-type furnaces. Portability of the equipment is one of the chief advantages of this method.

Electrical strip heaters of 100 to 220-volt rating have been used for local preheating of repairs in castings, for pipe and for pressure vessel joints especially for field welding. These must be carefully insulated at the terminals to avoid the danger of shock to workmen. Strip heaters, designed for 55-volt, a.c. transformers of 1000 amp. capacity have been used for the preheat of welded joints in plates of over 2-in. in thickness. These heaters are anchored to the plates approximately 4 in. from and parallel to the joint. They are then covered with a channel or inverted angle packed with dry insulating material. Since there is no arc interference it is unnecessary to switch off the preheat current during welding operations.

Another form of local preheating with radiated heat is used principally on pipe but has been used for circumferential joints in vessels as thick as $1^1/_4$ in. and with a circumference of 14 feet. One method utilizes oxidation-resistant wire of the Nichrome or Chromel type, insulated with ceramic beads of the type use on thermocouple leads. Using 8-gage wire, approximately 30 ft. of wire can be used to

Table 2—Construction Code Requirements for Thermal Stress Relief

Code	Mandatory Stress Relief	Conditions Specified
	Drums, Shells, Etc.	
ASME, Sect. I, Power Boilers, 1948	Paragraph P-108 requires S. R. of all fusion-welded pressure parts with some exceptions. Includes drums, manifolds, headers, etc.	(1) Heat up to at least 1100°F., and up to 1200°F., or higher if it can be done without distortion. Bring up slowly, hold at least 1 hr. per in. of thickness and cool slowly to a temperature not exceeding 600°F. (2) Local S. R. circumferential joint requires heated band six times plate thickness on each side of joint. (3) Nozzles and attachments may be locally S. R. if heated band 12 times shell thickness wider than attachment. (4) For piping and tubing the heated band shall be three times width of widest part of weld groove and not less than twice weld reinforcement.
	Welded Connections, etc.	
	Paragraphs P-112 and P-113, require S. R. of circumferential joints of pipe, tubes, headers if carbon steel over ⅜-in. nom. thickness or C-Mo (0.20% max.) over ⅜-in. nom. thickness.	Same as ASME P-108—(4) above.
	Paragraph U-68 Vessels	
ASME, Sect. VIII, Unfired Pressure Vessels, 1948	Paragraphs U-13(c), U-68, U-76 and U-200 require S. R. of all fusion-welded pressure parts.	Same as ASME P-108—(1), (2), (3), (4).
	Paragraph U-69 Vessels	
	Paragraphs U-13(c), U-69, U-76 and U-201 require S. R. of: SA302 steel in all thicknesses; SA202 Gr. A. SA203, SA204, SA225, SA299 and SA301 in all thicknesses 0.58 in. and over; SA212 in all thicknesses over 1 in., and in all thicknesses 0.58 in. and over and also 1 in. and less which are more than (D + 50)/120, where D = inside diameter; all other permissible steels over 1¼ in. thick and in all thicknesses 0.58 in. and over and also 1¼ in. and less which are more than (D + 50)/120.	Same as ASME P-108—(1), (2) (3), (4).
	Paragraph U-70 Vessels	
	No S. R. required on vessels built under this paragraph.	
	Pressure Parts	
ASME, Sect. III, Boilers of Locomotive, 1947	Paragraphs L-102, L-107 require S. R. of all fusion-welded pressure parts.	Same as ASME P-108—(1), (2) (3), (4).
	Unfired Welded Pressure Vessels	
API-ASME Code for Unfired Pressure Vessels for Petroleum Liquids & Gases, 1943	Paragraphs W-318.1, W-318.2, W-462, W-463 require S. R. for ASTM A212 and A225 when plate thickness at joint exceeds 1 in. or is less than 1 in. but exceeds (I.D. + 50)/120 where I.D. is inside diam. in in. with a lower limit of 20. Also if steel is not of firebox quality. Also if steel has a C content greater than 0.31%. Other permissible steels require S. R. if over 1¼ in. or if exceeds (I.D. + 50)/120 as above. W-318.2 for joint not requiring S. R. (under W-318.1) allows a joint efficiency factor of 1.06 for stress relieving compared with a factor of 1.0 if not stress relieved.	(1) Requires heating to 1100° F. min., holding 1 hr. per in. of max. metal thickness with heating rate of 400°F. and cooling rate of 500°F. divided by thickness in in.; 500°F. max., above 600°F. (Where 1100°F. is impractical allow 2 hr. at 1050°F., 3 hr. at 1000°F., 5 hr. at 950°F., or 10 hr. at 900°F.). During heating, max. temp. variation of 250°F., in 15-ft. length. During holding time, max. variation 150°F. throughout portion being heated. (2) If vessel is heated in sections requires overlap of 5 ft. and max. temp. gradient of 200°F. per ft. in plate outside of furnace. (3) For local S. R. of circumferential joints requires min. width of heated band to be 6 times plate thickness on each side of joint with max. gradient as in (2).

Table 2—Construction Code Requirements for Thermal Stress Relief (contd.)

Code	Mandatory Stress Relief	Conditions Specified
		(4) Controlled mechanical peening permitted for field-assembled vessels.
	Welded Structural Members	
AWS, Std. Spec. for Welded Highway and Railway Bridges, 1947	Paragraph 604(g) requires S. R. if any welding is done on material over 3-in. thick, or if material over 2 in. is welded to material half its thickness or less, except unimportant assemblies, like base plates.	Paragraph 609(b)—Where plans, drawings or Par. 604(g) requires S. R. the assembly shall be adequately supported in furnace and heated to 1100 to 1200°F. and held 1 hr. per in. of thickness of thickest part. The temperature is required to be uniform throughout cycle so that thermocouples attached to the anticipated hottest and coldest points will not vary more than 100°F. at any time. Thermocouple junctions shall not be in direct path of heating flames. Assembly may be removed from furnace at 600°F. or lower. All machining shall be done subsequent to heat treating.
	All Classes of Piping	
Am. Std. Code for Pressure Piping, ASA B31.1-1942 (Sup. No. 2, 1947)	Paragraph 628(a) (1) requires S. R. in carbon steel when nom. thickness is ¾ in. or greater. Paragraph 628(a) (2) requires S. R. in carbon steel of over 0.35% C or in C-Mol if the nom. thickness is ½ in. or greater. (In above or in slip-on flanges fillet welded, the thicker pipe or the highest C content shall determine necessity for S. R.)	(1) For furnace S. R. of entire pipe, temperature shall be 1100 to 1250°F. except where higher temperatures are required due to characteristics of material. Parts shall be heated slowly, held at temp. for the necessary period, which shall be 1 hr. per in. of thickness for carbon steel and 2 hr. per in. for C Moly, but in no case less than ½ hour. (2) For local heating of a circumferential band the width of the band shall be 3 times the width of the weld groove and 2 times the width of reinforcement, and the temperature shall be allowed to diminish gradually outward from the ends of this band.
	Marine Piping	
AWS Rules for Welding Piping in Marine Construction (Carbon Steel only)	Paragraph 9(a). All welded joints in Class 1 Piping over 2½-in. nom. pipe size shall be S. R. Paragraph 9(b). All complicated connections shall be furnace S. R. as a whole.	(1) The S. R. temperature shall be 1100 to 1200°F., with a holding time of 1 hr. per in. of pipe wall thickness, ½ hr. minimum. Rate of heating to be slow. Furnace heats shall be allowed to cool slowly to below 600°F.; local heats may be cooled under an insulating blanket. (2) Piping shall be designed to be free to expand in longitudinal direction when being S. R.
	Pressure Vessels, Piping & Machinery	
BU Ships, Navy Dept., Spec. S1-4, June 1941	Paragraph S1-4-p requires S. R. of the following: Class A1 fired and A2 and A3 unfired pressure vessels; Class B machinery welds; Class P-1 piping; seal welds in C or C-Mo of 0.35% C or greater and strength welds in C or C-Mo piping over 2-in. size; P-2 piping; seal welds in C steel of over 0.35% C and strength welds in C steel of over 0.25% C (for welded fabricated valves and manifolds); all welded rotating parts of electrical machinery.	(1) Stress relief temperature shall be 1100 to 1250° F. Furnace cooling required to 500°F. for C steels or 300°F. for air-hardening materials. (2) During heating and cooling temperature difference between any two points shall not exceed 100°F. Unless a temperature difference between any points is 75°F. or less the following rates of heating and cooling shall not be exceeded: 1-in. thickness, 200°F. per hr.; 2-in., 150°F.; 3-in., 100°F.; 4-in., 80°F.; 5-in., 60°F.; 6-in., 50°F

Table 2—Construction Code Requirements for Thermal Stress Relief (contd.)

Code	Mandatory Stress Relief	Conditions Specified
		(3) Up to 6 thermocouples shall be used on a furnace charge. The hot junction shall be fastened to the work. Recording pyrometric equipment shall be employed. (4) For local S. R. of pipe at least two thermocouples shall be used, with a two-point recording potentiometer, the hot junctions to be separated by a distance equal to the O.D. of the pipe. The weld shall be in the center except for flange to pipe joints where the flange side thermocouple shall be a min. of 2 in. from the weld. (5) For local S. R. the rate shall not exceed 40°F. for any 5-min. period. Soaking shall be at 1150°F. ± 50°F. for 1 hr. per in. or fraction of inch. Carbon-moly pipe shall be heated to 1100 to to 1175°F., held 1 hr. and cooled at a maximum rate of 125° F. per hr. to 500°F., below which it may be cooled in still air.

ASME Boiler Code Interpretations (March 1949) Case No.	Subject	Conditions Specified
824	Permission to fabricate boiler of seamless headers.	(Requires S. R. of headers after welding tubes or cross headers.
896	Permission to fabricate Fusion Welded Vessels of Clad materials SA263, 264, 265.	Subject to the S. R. requirements of Section VIII except S. R. is mandatory for SA263 Cr clad steels (except for Gr. 0 and A, with 0.08 %C max. when they are welded with austenitic electrodes).
897	Fusion-welded vessels of Chromium-Nickel Steel as such or with Cb, T or Mo. SA240 Grades S, M, C or T. Grade — Type — Treatments: S 304 (a) ... (c); M 316 (a) ... (c); Mc 316 Cb (a) (b) ...; C 347 (a) (b) (c); ... 321 (a) (b) (c)	(1) Where heat treatment is required it shall be of the completely welded vessel. (2) U-69 vessels over ½-in. thick and all U-68 vessels shall be heat treated. Recommends treatment (a) or (b) for other vessels—if not treated, requires treatment (a) or (b) applied to material as last heating operation. (3) *Treatment* (*a*)—Heat to 1900 to 2000°F. (1950 to 2050°F. for Grades M & Mc) hold 1 hr. per in. of max. thickness (½ hr., min.). Cool quickly and uniformly (3 min., max., from 1700 to 1000°F. for Grades S, M and Mc). Cautionary note regarding stress corrosion due to quenching stresses in certain chemical service. *Treatment* (*b*)—Heat to 1550°F. min. (1550 to 1650°F. for Grade T). Hold 2 hr. per in. of max. thickness, 2 hr., min. Cool in still air or in the furnace. *Treatment* (*c*)—Heat to min. of 1300°F. in accordance with Par. U-76 (same as P-108 (1). Special bend test required if applied below 1550°F. with Grades C or T.

Table 2—Construction Code Requirements for Thermal Stress Relief (contd.)

Case No.	Subject	Conditions Specified
905	Fusion-welded vessels of Cu-Cr-Ni Steel at service from −150 to 650°F.	Requires that the material be normalized before welding and stress relieved as provided in U-68.
941	Permission to construct welded unfired vessels to U-68 of Mn-Mo steel (modified A204-38).	(1) Plates over 5/8-in. thick shall be normalized at 1650 to 1700°F. (2) S. R. shall be as specified in Par. U-68, with slow cooling to less than 600°F. with the furnace doors closed.
985	Permission to construct fabricated flanges and necks by welding for boilers, piping and unfired pressure vessels.	(1) All flanges to Fig. UA-4(10), (11) shall be S. R. (2) Flanges to Fig. UA-3(6), (7) to be S. R. where the neck, pipe or shell to which attached is required to be S. R. by provisions of Pars. U-76 or P-112.
989	Permission to fabricate U-68 vessels of modified Types 410 and 430 straight chromium steels.	(1) Stress relief should preferably follow welding without intermediate cooling. (2) S. R. shall be 1350 to 1500°F. with soaking time sufficient to produce required ductility in weld. Cooling to 1000°F. shall not exceed rate of 100°F. per hr. Below 1000°F. cooling in still air permitted.
1065	Permission to fabricate built up fittings to U-68 except substitute a normalize for a S. R.	Allows normalizing of welded fittings (ells, tees, return bends, etc.). Testing required in normalized conditions.
1078	Permission to construct fusion-welded vessels lined with corrosion-resistant materials welded to components.	S. R. required for vessels with straight chromium steel (except SA263 Gr. O and Gr. A, with 0.08 %C max. when welded with austenitic electrodes).

conduct 100 amp. from a welding generator. Three such wires in parallel have been used with a 400-amp. welding generator. Temperature control is obtained by changing the voltage or the current at the machine as in welding. When heating by this method the electrically insulated wire is wrapped around the work, then well insulated thermally from the air by multiple layers of asbestos paper or by other high-temperature insulating material. Preheat can be obtained by a coil on each side of the joint; a third coil added over the completed weld can be used for stress relieving.

Induction heating, using 60-cycle transformers of suitable capacities specially built for this purpose, is probably the most common method of preheating pipe joints for welding. These transformers may be operated manually or with automatic controls which will maintain any temperature range or follow a predetermined time-temperature program. Coils may be heavy flexible copper cable insulated with asbestos, buss bars or water-cooled coils. Usually one or more layers of asbestos paper are wrapped around the pipe prior to placing the coil in position. Insulation need not be placed outside the coil. The heating current must be turned off during welding to prevent interference with the arc. This can be controlled by the welding circuit and thus can be made automatic.

Induction heating can also be obtained by the use of a laminated core inside a pipe or on the surface of a plate adjacent to a joint. This method has been used with movable coils preceding an automatic welding head along a pressure vessel joint.

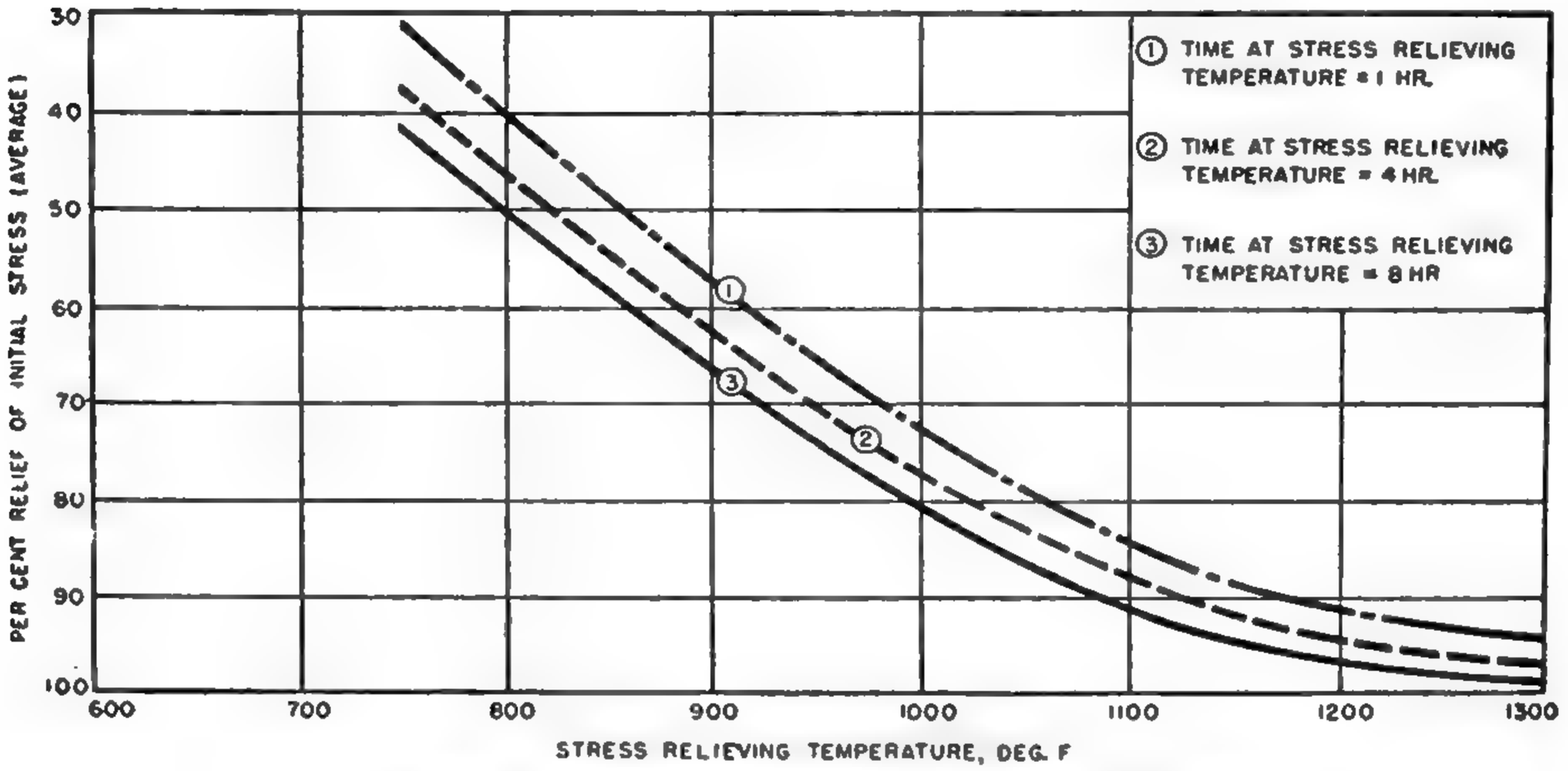
Postweld Thermal Treatments

Thermal Stress Relief.—C. R. Jelm and S. A. Herres have shown that the percentage relief of internal stresses is independent of steel type, composition and yield strength. The effects of varying time and temperature are shown in Fig. 4. It is interesting to note that temperature has a far greater effect in relieving stresses than the length of time the specimen is held at that temperature.

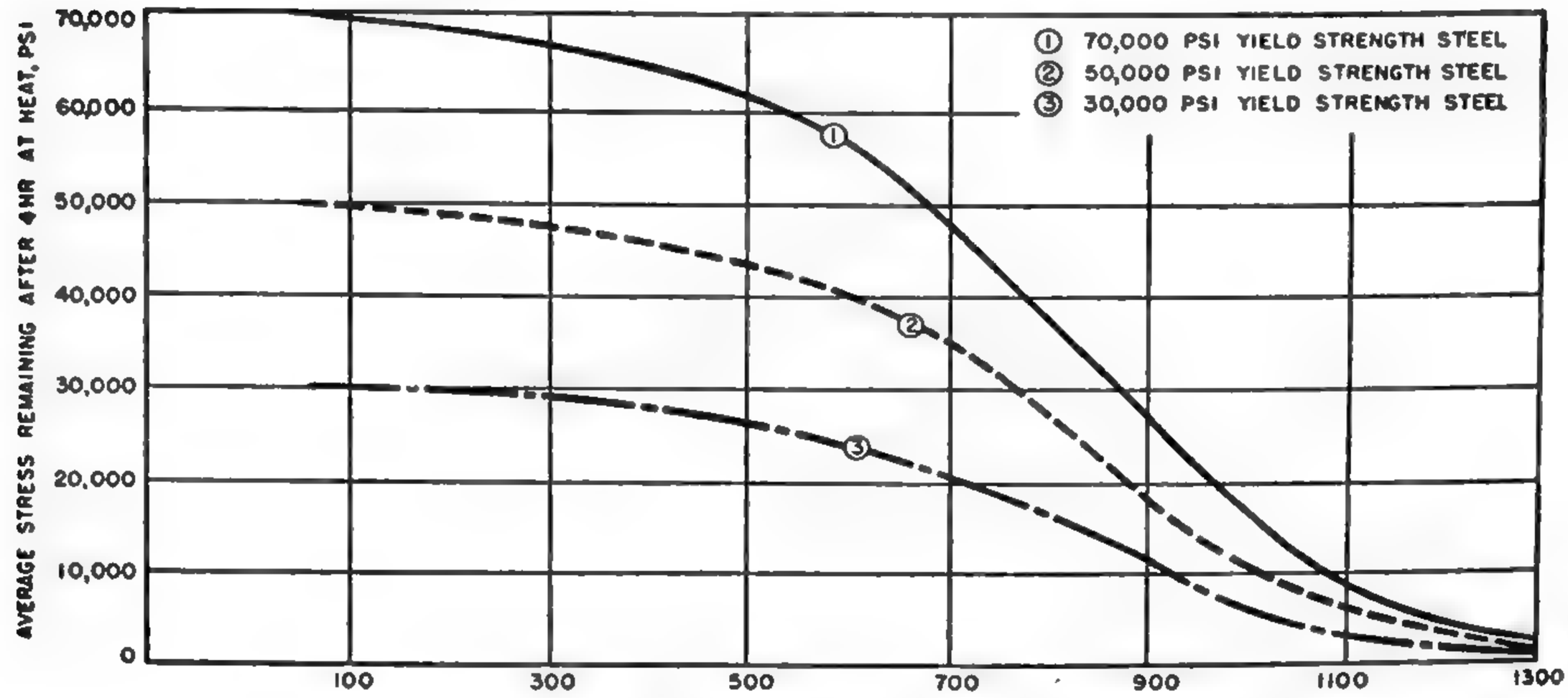
Thermal stress relief can be conducted

in any furnace suitable for heating the entire weldment. Figure 5 shows a pressure vessel ready for stress relief in a car-type, oil-fired furnace $13^1/_2 \times 13^1/_2 \times 80$ ft. in size. Figure 6 shows an assembly of chromium-molybdenum piping ready for stress relief in an oil-fired furnace 9×11 $\times$ 37 ft. in size. Sometimes only a portion of the weldment is heated if the structure is uniform in cross-section and the unheated ends are free to move and do not restrict the expansion of the heated part. By this method pressure vessels can be partly enclosed but extend beyond the furnace end and be stress relieved even though they are longer than the available furnace. Care must be taken that there is an overlap of the heated sections in the successive heats and that the temperature gradient is not steep enough to introduce excessive thermal stresses. Figure 7 shows the application of local thermal stress relief to a circumferential joint of a pressure vessel 16 ft. in diam.; the vessel is rotated to obtain uniform heating.

The length of time the weldment should be held at the maximum or soaking temperature depends on the thickness of the



(*a*) Stress-relief temperature vs. % total stress remaining.



(*b*) Stress-relief temperature vs. avg. stress remaining.

Fig. 4.—Effect of Temperature and Time on the Relief of Stresses

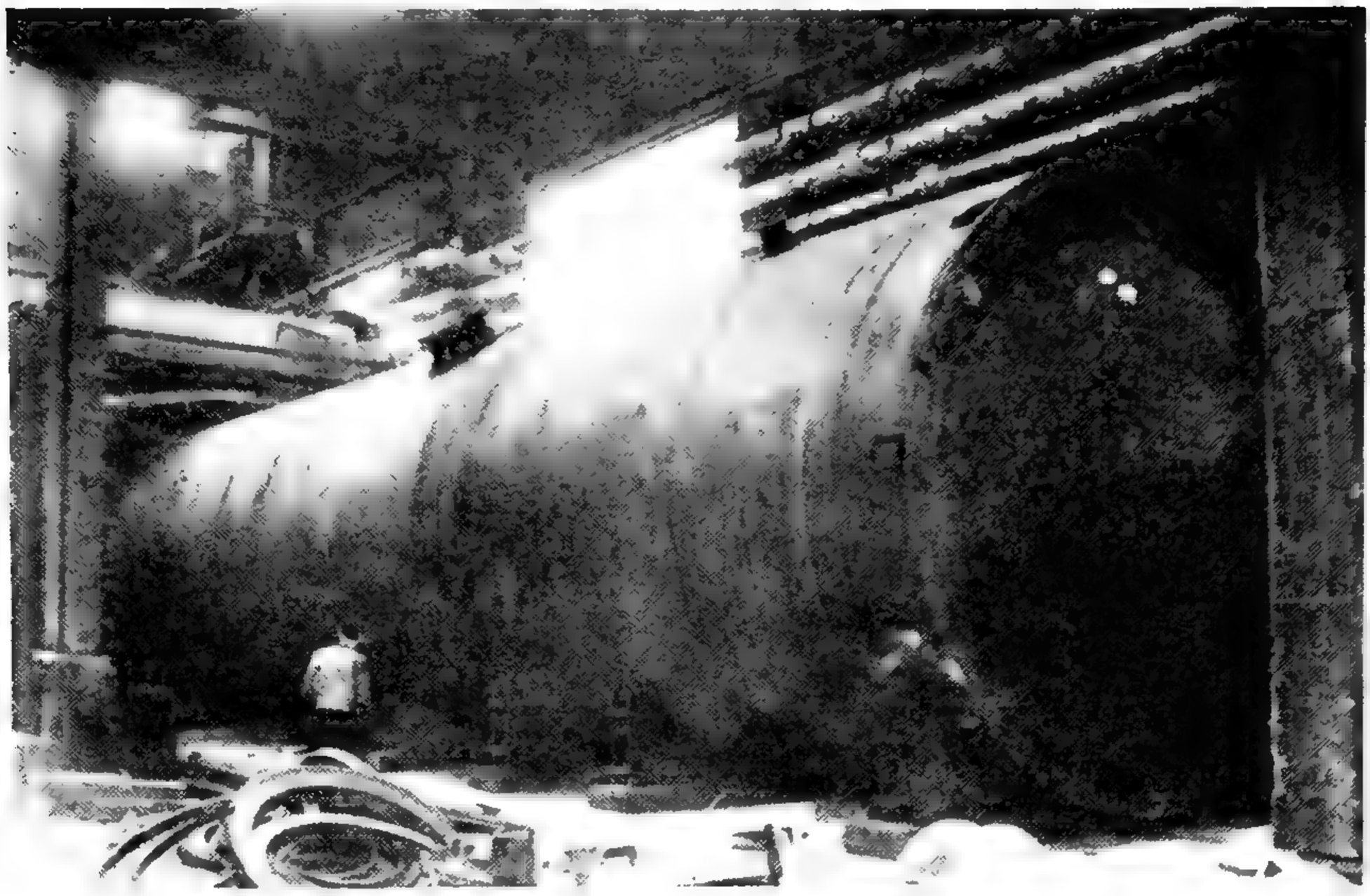


Fig. 5.—Pressure Vessel Ready for Thermal Stress Relief in a Car-Type, Oil-Fired Furnace

parts and the yield strength-temperature characteristic of the metal of which it is made.

Table 3 gives maximum temperatures and times at those temperatures per inch of maximum thickness for a number of metals and alloys. Adequate support of lighter parts must be provided, otherwise serious distortion may result.

Both the increase and reduction of temperature must be gradual and at a rate which will insure approximately uniform temperatures throughout. In general the greater the difference between the maximum and minimum thickness, the slower should be the rate of temperature change. Since other factors such as strength-temperature characteristics of the metal being treated and geometry of the parts are involved, an all-embracing formula for the maximum heating and cooling rates is not very satisfactory. The following rules can be used as an approximate guide for simple cases.

Case 1: Where the ratio of maximum to minimum thickness does not exceed 4

Table 3—Typical Thermal Treatments for Weldments

Material	Soaking Temperature, °F.	Time, Hr./In. Thk.
Carbon steel	1100–1250	1
C–½% Mo steel	1200–1325	2
1% Cr–½% Mo steel	1250–1350	2
2% Cr–½% Mo steel	1300–1375	2
2¼% Cr–1% Mo steel	1325–1400	2
5% Cr–½% Mo (Type 502) steel	1350–1400	2
9% Cr–1% Mo steel	1375–1425	3
12% Cr (Type 405) steel	1300–1350	1
12% Cr (Type 410) steel	1350–1400	2
15% Cr (Type 430) steel	1400–1450	4
Austenitic Mn steels	1900–2000, air cool	1
Austenitic Cr-Ni steels	1900–2000, air cool	1
Low alloy Cr-Ni-Mo steels	1100–1250	1
2 to 5% Ni steels	1100–1150	1
9% Ni steel	1000–1100	2
Monel	1100–1250	1
Inconel	1100–1250	1
Nickel	1100–1250	1
Cast iron	1050–1250	1

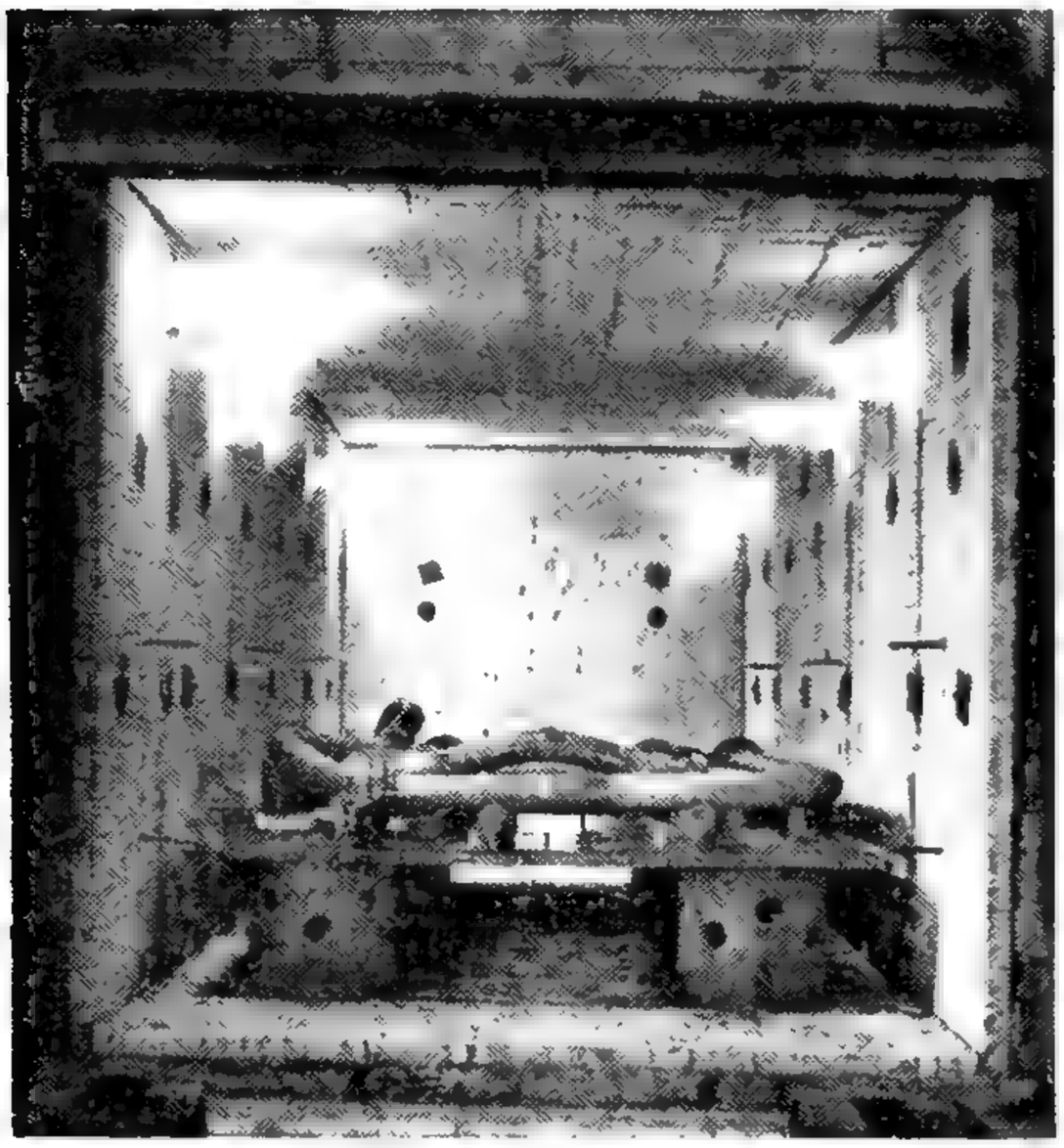


Fig. 6.—Chromium-Molybdenum Pipe Ready for Thermal Stress Relief in an Oil-Fired Furnace

to 1 heating and cooling rates should not exceed 400°F. per hr. divided by the maximum thickness in inches at the weld.

Case 2: Where the ratio of maximum to minimum thickness exceeds 4 to 1, heating and cooling rates per hour should not exceed: 1 in. thick—200°F.; 2 in.—150°F.; 3 in.—100°F.; 4 in.—80°F.; 5 in.—60°F.; 6 in.—50°F.

For complicated structures with members of widely varying thickness the safest procedure is to attach thermocouples to all critical sections and not permit more than 75°F. difference between any two sections.

The temperature at which a member may be withdrawn from the heating chamber depends upon a number of conditions. It must be remembered that a temperature differential of 100°F. in a rigidly fixed piece is equivalent to 20,000 psi. at temperatures below 600°F. It is therefore important that members having variable rigidity or restraint within themselves be reduced uniformly to the atmospheric or ambient temperature; otherwise distortion and new residual stresses will result. It is important that even simple vessels, such as drums of uniform thickness, be cooled uniformly and slowly if distortion and new stresses are to be avoided and the benefits of reduced hardness in the heat-affected zone are to be obtained. Thus a still air is very desirable after the furnace is opened and until the piece is fully cooled.

Pressure vessels of simple form and uniform thickness are frequently withdrawn at 600°F., or the furnace is opened at that temperature to permit more rapid cooling. This may safely be done if the air surrounding the vessel is sufficiently quiet to insure uniform temperature. More complex assemblies are cooled to a lower temperature (in extreme cases to 200°F.) before opening the furnace.

Local thermal stress relief is also used on circumferential joints in pressure vessels and, more commonly, in pipe. Figure 8 shows the local stress relief of a welded

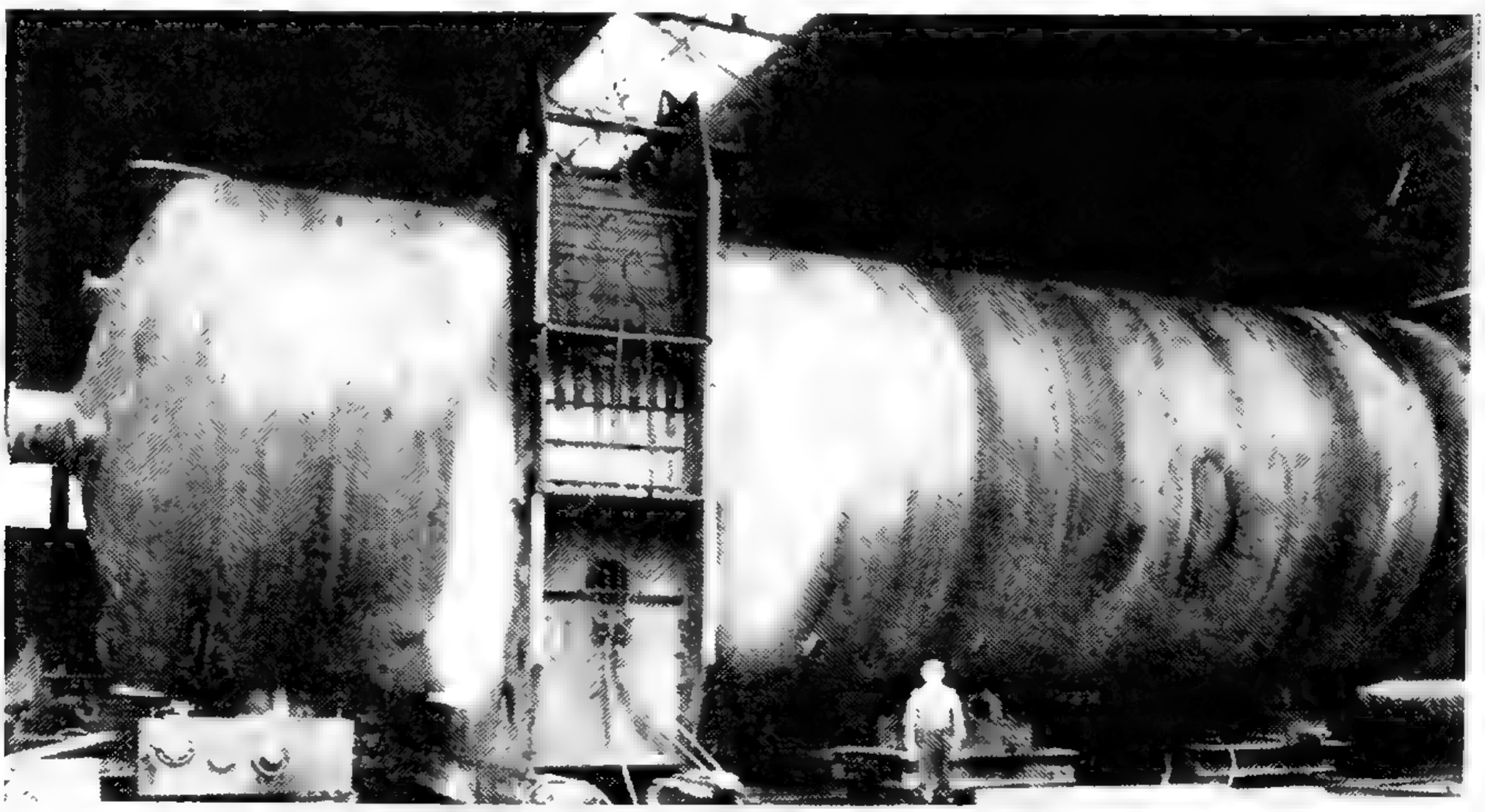


Fig. 7.—Local Stress Relief of Circumferential Joint in 16-Ft. Diam. Pressure Vessel

pipe joint in the field by means of a 60-cycle induction heating element. Again the temperature gradient should be controlled and restriction of movement should be minimized. Local stress relieving can be dangerous if misapplied. Complex structures can be fractured due to unequal expansion, or the structure can have increased locked-up stress following the treatment. Attempts to locally stress relieve the longitudinal shell joints of pressure vessels have resulted in fractures at the ends of the joints caused by expansion stresses. This could be expected if it is considered that a section 10 ft. long expands approximately $^3/_4$ in. at the stress-relief temperature.

Oxidation of the surface at temperatures up to 1200°F. for ordinary holding times at temperature is not severe. However, a minimum of excess air in the fuel mixture consistent with good combustion should be maintained. Sometimes it is advantageous to machine subassemblies which necessitates stress relief of the finished surface. This is often true of flanges on pressure vessel nozzles. Protection of these surfaces can be obtained by covering with fire clay, asbestos or by the use of a scale-resistant paint. Scaling of closed vessels can be reduced on the inside by closing all openings and leaving a vent for the escape of the expanding air. In extreme cases where the insides of vessels must be entirely clean and are not accessible for cleaning after stress relief, nitrogen has been used to flush out the interior air and maintain an inert atmosphere during heat treatment.

Controlled Low-Temperature Stress Relief.—This process was developed during the last war, in an attempt to provide means for reducing locked-up weld stresses in ships and other weldments too large to be stress-relieved in a furnace. This method is not a thermal method in the sense of stress relief through relaxation of elastically-strained material by plastic flow induced through a lowering of the yield strength. It consists of progressively heating two bands, one on each side of a welded joint, while keeping the joint itself relatively cool. The theory of this procedure is that the two zones of compression, which normally balance the tension band along the axis of the weld, are made to expand thermally whereas the tension band which remains cool expands not at all or at least very little thermally. Since the volume of metal which is made to expand thermally is much greater than the volume of metal in the tension band, the force of its expansion mechanically stretches the tension band beyond the yield point. On cooling, the two heated bands contract thermally and allow the cold central band to contract elastically thus relieving the locked-up tension in it. By properly controlling the amount of thermal expansion it is possible, theoretically at least, to reduce the locked-up stresses in the weld to any desired value, or even convert it to compression.

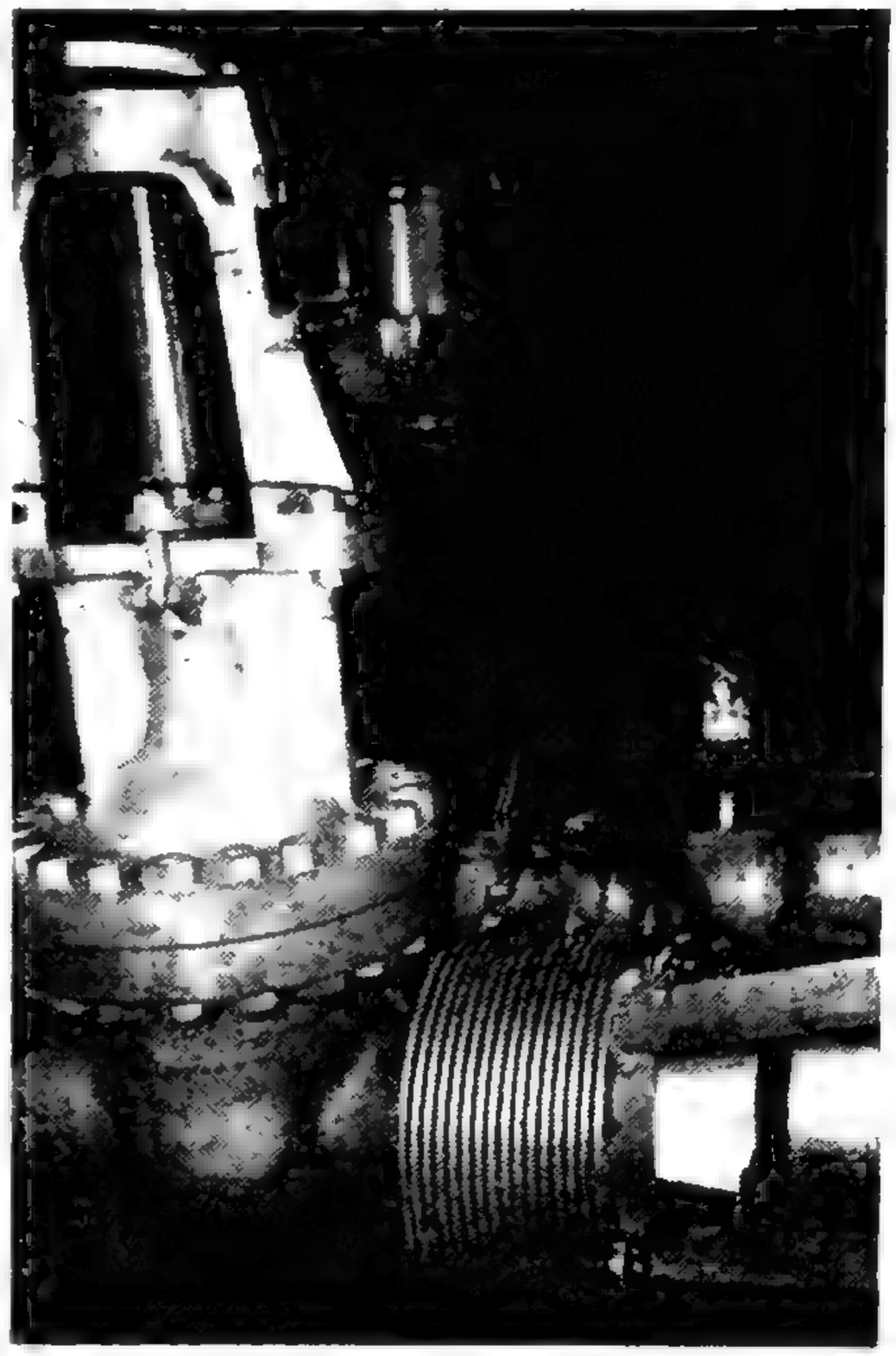


Fig. 8.—Welded Pipe Joint being Stress Relieved in the Field by Means of Induction Heating Element

There is no question that when properly used this method will reduce locked-up longitudinal stresses in simple butt welds by a very substantial amount. Its effect on the metallurgical properties of the weld metal or of the heat-affected zone, and therefore its value in improving the service properties of the welded joint, has not been definitely established.

Normalizing.—Normalizing of steel is generally performed for the purpose of re-

fining and unifying the grain size after casting, forging, hot bending of pipe or other hot working operations. Where this is necessary to provide required properties in the materials becoming a part of a weldment (for example, heavy casting or ASTM A201 and other plates over 2 in. in thickness) it is generally performed prior to welding to provide the superior properties of the refined structure to withstand the welding stresses. Stress relief of these components after they are welded together should follow normalizing if the carbon or alloy content of the material causes it to be air hardening. Normalizing is generally performed on ferritic material for service at temperatures below —20°F.

Where special properties are required, weldments sometimes are normalized. Since the probability of warpage of the weldment is great, special handling equipment for the hot structure is required.

One of the metallurgical benefits of normalizing completed weldments is the development of a more homogeneous structure across the joint. The treatment tends to coarsen the refined heat-affected zone and erase the definite line of fusion between weld and base metal. This has been found advantageous prior to stretching of cylinders, which is sometimes done for sizing purposes and for increasing the yield strength of the cylinder wall. Normalizing of completed weldments and of weld joints (locally) has also been used to inhibit the formation of chain graphite in carbon-molybdenum steam piping operating at temperatures above 900°F. Perhaps the most common use of normalizing in weldments is to improve impact strength at subzero temperatures in low-alloy materials containing nickel, copper-chromium-nickel or aluminum-killed carbon steel. It is customary to temper or stress relieve following normalizing to remove stresses and reduce hardness.

Full Annealing.—Full annealing serves to erase the metallurgical notch present in any joint since it is similar in action to normalizing, except that the slow cooling to below the critical transformation range results in a larger grain size and produces maximum softness in most ferrous materials. If the slow cooling is continued to near ambient temperature the result is a soft, dimensionally stable structure.

Annealing following welding is most common in the treatment of air-hardening materials. The martensitic chromium-molybdenum and straight chromium steels are generally postheated to 1550 to 1650° F., held at the temperature for a period of 2 hr. or more per in. of thickness, and cooled at a maximum rate of 25 to 50°F. per hr. to a temperature below the critical range. (Since the transformation temperatures are suppressed in the cooling cycle the rate of cooling is generally controlled to 1100°F. or below.) The martensitic chromium steels are subject to impairment of physical properties, especially impact resistance, when heated in the range of 800 to 1000°F. due to a precipitation phenomenon. For this reason it has become common practice to cool rapidly in air through this range. The use of molybdenum in the lower chromium steels almost entirely inhibits this *temper brittlement,* thus eliminating the necessity for rapid cooling with its possibility of warpage and the introduction of residual stress due to variations in cooling rates in different parts of the structure.

Quenching and Tempering.—Quenching and tempering are sometimes necessary to obtain special properties in either weld metal or base metal. Dies are sometimes repaired or altered by welding. If extensive machining of the weld area is required the repaired die may be annealed following welding, machined and then heat treated to conform to the base material. Selection of a weld deposit identical with the die steel removes the question of variations in hardness. Most surfacing applications are preformed with a deposit specified to provide the required hardness in the as-welded condition.

Solution and Precipitation Treatments.—Solution and precipitation treatments are used to develop the *aged* properties of certain types of alloys. Aging is believed to be a precipitation of microscopic or submicroscopic particles within the metal crystal, thus increasing the yield and ultimate tensile strengths of the alloy.

The application of solution and precipitation heat treatments subsequent to welding is quite frequently done when welding and brazing the heat-treatable aluminum alloys and the practice is only limited by the availability of heat treating equipment. There is a very substantial increase in both tensile strength and yield strength across the weld when the parts are solution heat treated and aged after welding. The tensile strength of welds in aluminum alloys

up to 1-in. thick can be increased to the tensile strength of the base material by such heat treatment. The ductility, however, is not improved substantially and the application of postweld heat treating does not eliminate the necessity for testing prototypes of welded structural assemblies to make sure that they possess adequate ductility or elongation. The heat-treating procedure is usually about the same as used for unwelded parts; the quenching after solution heat treating is varied to suit the geometry of the piece. The quenching medium may be cold water, hot water, water spray or an air stream depending on the base metal and the complication of the parts. The above quenching mediums are listed in the general order of preference from the standpoint of getting maximum resistance to corrosion and maximum mechanical properties. They are listed in the reverse order of preference from the standpoint of distortion from quenching. Specific applications require judgment in choosing the best overall procedure. Precipitation hardening by natural or artificial aging of welds is accomplished with exactly the same times and temperatures proper for the base metal. This phase is not complicated and no distortion is obtained in the process.

The copper-nickel-molybdenum low-alloy steels may have satisfactory properties if subjected to a precipitation treatment without a prior solution treatment since the as-rolled condition is often the equivalent of a solution treatment (air cooling from above the upper critical temperature). Most consistent results will be obtained, however, if the material is subjected to both the solution and the precipitation treatments. Precipitation is generally performed by holding at temperatures of 900 to 1000°F. for a time of 1 to 4 hr., depending on the thickness of the section. Ordinarily for the welding of this material no attempt is made to match the base metal in chemistry, the weld metal composition rather being selected to have similar physical properties when subjected to the heat treatment required by the base metal. It is considered desirable to perform the solution as well at the precipitation treatment following welding since the welding stresses and the heat-affected zone are obliterated during the solution treatment. Where solution treatment of the entire weldment is impracticable the components may be so treated and the completed weldment can then be given the lower temperature precipitation treatment to develop the desired strength. When this procedure is followed it should be remembered that only partial relief of stress is obtained, and that an electrode should be selected to give a weld metal which will not be excessively hard (and consequently low in ductility) when subjected to the relatively low-temperature draw.

Molybdenum-vanadium-chromium base material has been closely matched in chemical content by the weld desposit in order to obtain the specific high temperature properties of the base material. The base metal only is generally solution treated (1950°F., 4 hr. air cooled); with the aging treatment (1200 to 1325°F., 4 hr. minimum furnace cooled) being performed following welding.

The terms *solution* and *precipitation* are also applied to the treatment of austenitic chromium-nickel steels. Carbon will come out of solution in these steels when they are heated in the 800 to 1800°F. range and precipitate in the grain boundaries as chromium carbide. This reaction causes a depletion of chromium near the grain boundaries, making the steels sensitive to certain chemical attack, known as intergranular corrosion, in these areas. A solution treatment involves heating the material within the range of 1900 to 2000°F. for a half hour or longer and cooling rapidly through the sensitizing temperature range to avoid reprecipitating carbides.

MECHANICAL TREATMENTS OF WELDMENTS

Peening.—Although peening has been used in conjunction with welding for several decades, factual data concerning its application and results to be expected are not common. The Welding Research Council, using the facilities of the American Bureau of Shipping, is now conducting a thorough investigation of the factors involved in peening. The API-ASME *Code for Unfired Pressure Vessels,* 1942 Addenda permits peening to reduce stress in welded joints as an alternative to thermal stress relief (Par. W-463), controlling the degree of peening by maintaining a nearly constant dimension between

benchmarks across the joint. Somers examined the effect of peening temperatures on the properties of E6020 weld metal. As would be expected an increase in hardness was observed in the worked metal, especially in the top layer peened at 600°F. which reached 99 Rockwell B, compared with a hardness of 76 Rockwell B in an unpeened weld.

The primary purpose of peening is to promote plastic strain, that is elongation along one or two axes, with corresponding reduction along the remaining axis or axes, by applying compression along the axis in which the reduction is to take place. To be most effective compression should be applied uniformly or simultaneously over the entire straining area, and since this is obviously impossible the blows should simulate this condition as closely as possible. Quick light blows applied as rapidly as possible with a round-nosed tool, preferably an air-hammer, offer the best compromise. Considerable skill is required to distribute the blows as uniformly as possible since localized overpeening can result in excessive hardening, flaking and even cracking. Peening should be preceded by a cleaning operation in order to prevent entrapment of slag and flux. To prevent cracking, peening should be done at as high a temperature as possible, while distortion is best controlled by peening cold metal. Certain alloy weld metals have low ductility in the blue-brittle range (300 to 700°F.) and even higher and these should always be peened cold.

Peening is most effective on light weld deposits. Peening of weld deposits over $^{3}/_{16}$-in. thick is of doubtful value in most cases and should not be attempted on deposits $^{1}/_{4}$-in. thick or thicker.

Recent investigations indicate that peening does little to reduce residual stresses unless all weld passes including the final pass and the base metal adjacent to it are peened after the weldment has cooled down to ambient temperature. Since most codes prohibit peening of the final pass for several reasons, one of them being to permit visual detection of cracks, the value of peening to control residual stresses is doubtful.

Inasmuch as the subject of peening has not been scientifically studied, the API-ASME *Code for Unfired Pressure Vessels* prescribes a method for checking the effectiveness of a peening procedure in an actual welding operation. According to to this code, punch marks should be made on opposite sides of the weld and the distance between these marks kept within $\pm$ $^{1}/_{32}$ in. by peening during the welding of the seam, the first measurement being made after two layers of weld metal have been deposited. If the peening has been executed so as to hold the deviation in distance between punch marks to a minimum until the weld has been built to a depth of $1^{1}/_{4}$ to $1^{1}/_{2}$ in., the same degree of peening may be applied safely to the remainder of the weld.

Peening of resistance welds to reduce distortion of sheet-metal parts is usually done with a mechanically-operated trip-hammer using flat wide dies for both the hammer and supporting anvil. Since the welds must be backed up by rigid anvils immediately under the hammer blow, the parts are usually moved through a stationary hammer. Metal near welds is usually peened as well as the weld itself.

Proofstressing.—Recent investigations indicate that uniform loading of weldments tends to decrease longitudinal locked-up stresses by the amount of loading. Thus if a non-stress-relieved weldment consisting of two plates joined by a butt weld is loaded in tension parallel to the axis of the weld until a nominal state of tensile stress of 10,000 psi. exists throughout the weldment, the residual longitudinal stress in the weld will be reduced by 10,000 psi. It must be noted that to result in effective relaxation of stresses the loading must produce uniform stress throughout the weldment, since a non-uniform stress may result in worse locked-up stresses than the original ones caused by welding.

Cylindrical and spherical pressure vessels can be readily proof-stressed by hydrostatic loading. In cylindrical vessels hydrostatic loading produces circumferential stress approximately double the longitudinal stress so that relief of residual stress in longitudinal welds will be only half the relief in circumferential welds.

Proofstressing of weldments of more complex geometry usually presents considerable difficulties and is therefore seldom attempted. Proofstressing often serves as a final fabricating operation by smoothing out irregularities of form by plastic straining, so that under subsequent service conditions, the strains will be wholly elastic and within safe limits.

BIBLIOGRAPHY

1. *Weld Hardening of Carbon and of Alloy Steels*, H. R. French and T. N. Armstrong, The Welding Journal Res. Suppl., October 1939.

2. *Metal Processing*, O. W. Boston, John Wiley & Sons, 1941.

3. *Weld Hardening and Steel Composition*, A. Edson, Metals and Alloys, June 1942.

4. *Effect of Peening Temperature on Weld Metal*, R. E. Somers, The Welding Journal Res. Suppl., November 1943.

5. *Peening—Its Effect on Relief of Residual Stresses, Distortion and Mechanical Properties of Welds*, A Review of the Literature to July 1, 1943, W. Spraragen and M. A. Cordovi, The Welding Journal Res. Suppl., March 1944.

6. *Stress Relief of Weldments for Machining Stability*, J. R. Stitt, The Welding Journal Res. Suppl., June 1945 and January 1946.

7. *The Problem of Fracture*, J. H. Hollomon, American Welding Society, 1946.

8. *Controlled Low-Temperature Stress Relieving*, T. W. Greene and A. A. Holzbaur, The Welding Journal Res. Suppl., March 1946.

9. *A Method for the Measurement of Residual Welding Stresses*, J. L. Meriam, E. Paul DeGarmo and Finn Jonassen, The Welding Journal Res. Suppl., June 1946.

10. *Residual Stress in Intersecting Butt Welds*, J. L. Meriam, E. Paul DeGarmo and Finn Jonassen, The Welding Journal Res. Suppl., August 1946.

11. *The Effect of Weld Length Upon the Residual Stresses of Unrestrained Butt Welds*, E. Paul DeGarmo, J. L. Meriam and Finn Jonassen, The Welding Journal Res. Suppl., August 1946.

12. *The Influence of Heat-Treatment Upon the Susceptibility to Graphitization of High-Chromium-Deoxidized Carbon-Molybdenum Steel*, F. Eberle, Trans. Am. Soc. Mech. Engrs., August 1946.

13. *Residual Stress Relief of Steel Castings and Weldments*, C. R. Jeln and S. A. Herres, American Foundryman, September 1946.

14. *The Effect of Peening Upon Residual Welding Stresses*, E. Paul DeGarmo, J. L. Meriam, and Finn Jonassen, The Welding Journal Res. Suppl., October 1946.

15. *Redistribution of Residual Welding Stresses by Tensile Louding Along a Unionmelt Weld Joining Two 3-Ft. × 12 Ft. × 1-In. Plates*, Finn Jonassen, E. Paul DeGarmo and J. L. Meriam, The Welding Journal Res. Suppl., October 1946.

16. *Arc Atmospheres and Underbead Cracking*, P. J. Rieppel and M. W. Mallet, The Welding Journal Res. Suppl., November 1946.

17. *The Fracture of Metals*, M. Gensamer, E. Saibel and J. T. Ransom, American Welding Society, 1947.

18. *Some Tests of Large Welded Structures*, J. L. Meriam, E. Paul DeGarmo and R. C. Grassi, The Welding Journal Res. Suppl., May 1947.

19. *The Design and Methods of Construction of Welded Steel Merchant Vessels*, Final Report, Board of Investigation convened by order of The Secretary of the Navy, The Welding Journal Res. Suppl., July 1947.

20. *The Effect of Temperature and Welding Conditions on the Strength of Large Welded Tubes*, G. E. Troxell, E. R. Parker, H. E. Davis and A. Boodberg, The Welding Journal Res. Suppl., February 1948.

21. *The Structural Strength of the Welded Joint*, G. S. Mikhalapov, The Welding Journal, March 1948. Also available in booklet form.

22. *Cleavage Fracture of Ship Plates as Influenced by Size Effect*, H. W. Wilson, R. A. Hechtman, W. H. Bruckner, The Welding Journal Res. Suppl., April 1948.

23. *Cleavage Fracturing and Transition Temperatures of Mild Steel*, A. B. Bagsar, H. E. Davis, E. R. Parker and G. E. Troxell, The Welding Journal Res. Suppl., April 1948.

24. *State of Stress in Arc Welds Made Under Transverse Restraint*, E. F. Nippes and W. F. Savage, The Welding Journal Res. Suppl., July 1948.

25. *The Comparative Behavior of Mild Steel Welds Made with E6010 and E6016 Electrodes*, F. W. Daniels, F. S. Gardner and R. M. Rood, The Welding Journal Res. Suppl., September 1948.

26. *Tests of Large Welded Steel Box Girders*, A. H. Stang and B. S. Jaffe, The Welding Journal Res. Suppl., March 1949.

27. *Stress Corrosion in Naval Brass Weldments*, Bela Ronay, The Welding Journal, April 1949.

28. *Preliminary Results of Weld Peening Investigations*, J. Lyell Wilson, The Welding Journal Res. Suppl., March 1950.

CHAPTER 44

STATISTICAL CONTROL OF WELD QUALITY

INTRODUCTION

THE TERM *statistical analysis* generally refers to the handling and analysis of numerical data. More specifically, statistics deals with the analysis of the *variability* of repetitive data. This useful technique has found extensive application in many fields where repetitive data must be gathered, analyzed and interpreted. The application of statistics to control weld quality will be evident to anyone familiar with the details and problems encountered in welding production and research.

It is not the intention of this chapter to trace the theory and mathematical analysis which lie behind the practical statistical procedures which will later be described, but rather to describe in simple terms the philosophy behind statistical procedure and to present briefly several successful statistical methods in such a manner that anyone who wishes to apply them to his own manufacturing process can do so. Methods will be presented for quantitatively expressing *quality* and *variability*, making it a relatively simple matter to make predictions and estimates which are mathematically as well as economically sound. Emphasis will be placed on methods closely allied to the problems encountered in production inspection and quality control at a sacrifice to other important statistical fields such as correlation, tests of significance, and design of research experiments.

The basis for modern statistical theory dates back to the eighteenth century with the discovery of the *Normal Curve* by the French mathematician, De Moivre. This curve was later rederived independently by LaPlace and the famous astronomer, Gauss, who found that this distribution could be used to describe variations of *errors of observation*. Actual statistical use of the Normal Law Integral starts with the work of Gauss. Important contributions were made to the science by workers in many fields, and in 1924 Dr. Walter Shewhart introduced the *control chart* and a new attitude of thought in terms of the control of quality of manufactured products. The work of Dr. Shewhart and his associates of the Bell Telephone Laboratories gave tremendous impetus to the industrial use of statistics in quality control work. During World War II, with the encouragement of the Office of Production Research and Development of the War Production Board, many more companies became familiar with the advantages of efficiency and economy to be gained with the use of statistical quality control.

VARIABILITY

Variability appears to be an inherent characteristic of all processes, both those occurring in nature and those in manufacturing. The purpose of statistical analysis is largely to examine this variability and to detect when and to what extent extraneous factors enter to alter the variability pattern.

Types of Variation

There are essentially two types of variation treated by statistical analysis. The first type of variation is described by Gauss's classical law of errors of observations and is used to analyze errors of measurement for a particular test method. If observations or measurements of a single phenomenon or of a single physical object are made with sufficient refinement, there will be in general as many different

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values as observations. If the observations are randomly selected and made under essentially the same conditions, it is usually assumed that the distribution of observations can be described by relatively simple mathematical relationships.

usually small compared with actual variations in quality characteristics. In view of these two types of variation one is forced to the conclusion that the absolute value of any quality characteristic must be unknown.

Table 1—Typical Frequency Distribution Analysis

Shear Strength of Single Spot Welds, 24S-T Alclad Aluminum Alloy, 0.040 to 0.040-In. Sheet

Class Interval, Lb. ($i = 20$)	Mid-Point, X_m, Lb.	Number in Interval, f	Cumulated No.	$d = \frac{X_m - X'}{i}$	fd	fd^2
325–344	334.5	1	1	−9	−9	81
345–364	354.5	1	2	−8	−8	64
365–384	374.5	6	8	−7	−42	294
385–404	394.5	7	15	−6	−42	252
405–424	414.5	16	31	−5	−80	400
425–444	434.5	62	93	−4	−248	992
445–464	454.5	80	173	−3	−240	720
465–484	474.5	108	281	−2	−216	432
485–504	494.5	136	417	−1	−136	136
505–524	514.5 = X'	86	503	0	0	0
525–544	534.5	104	607	+1	+104	104
545–564	554.5	75	682	+2	+150	300
565–584	574.5	31	713	+3	+93	279
585–604	594.5	25	738	+4	+100	400
605–624	614.5	14	752	+5	+70	350
625–644	634.5	4	756	+6	+24	144
645–664	654.5	0	756	+7	0	0
665–684	674.5	0	756	+8	0	0
685–704	694.5	1	757	+9	+9	81
		$\Sigma f = 757 = n$			−1021	$\Sigma fd^2 = 5029$
					+ 550	
					$\Sigma fd = -471$	

Computation of the mean (Formula 5)

$$\bar{X} = X' + \left(\frac{\Sigma fd}{n}\right) i$$

$$= 514.5 - \frac{471}{757} \times 20$$

$$= 502.1 \text{ lb.}$$

Computation of standard deviation (Formula 13)

$$\sigma = i\sqrt{\frac{\Sigma fd^2}{n} - \left(\frac{\Sigma fd}{n}\right)^2}$$

$$= 20\sqrt{\frac{5029}{757} - \left(\frac{471}{757}\right)^2}$$

$$= 49.8 \text{ lb.}$$

The second type of variation describes the actual quality distribution of a material. Simply, no two things are ever made exactly alike. The magnitude of variation depends upon the details of the process, for example: natural material variation, operator skill, machine variability, gage wear. A product characteristic which is the result of hand operations may have relatively large variations (size of weld, spot weld spacing). On the other hand, variations which are the results of machine operations may be comparatively small (gage blocks, gears, ball bearings). Obviously, with any manufactured product, variation is merely a matter of degree.

In industrial quality control, variations of the first type are seldom considered since variations of measurements are

Statisticians refer to the group of observations resulting from the variations of repetitive data as a *frequency distribution.* Any one (or none) of the observations from this distribution may be the true value or true average value. It will clarify thinking in terms of engineering materials and processes in general if all measurable characteristics are visualized in this manner. *The variability of a measurable characteristic is as much a property of the object or the method of measurement as its tensile strength, electrical resistance or surface finish.*

Attributes and Variables

The simplest type of inspection consists of separating the good from the bad. A good deal of material is inspected in this manner for economic reasons since many

quality characteristics are easily adapted to mechanical inspection of the go no-go type. Many quality characteristics which are difficult to express in quantitative terms can be separated in this manner, for example: seams, cracks or porosity in welds. This type of inspection is called *inspection by attributes*. An object which is unacceptable is called *defective* as opposed to an object which is satisfactory or *effective*. The ratio of the number of pieces that are defective to the total number of pieces under consideration is the *fraction defective*. Inspection by attributes is usually non-destructive.

A second type of inspection is *inspection by variables*. The quality under consideration is measured on some continuous scale and quantitatively expressed. The test, particularly in welding, is often destructive. Inspection by the method of variables results in an appreciable increase in efficiency as reflected by a smaller required sample.* Economically, the destruction of good pieces in the sample may outweigh the advantage of a smaller sample.

* *Sample* is defined as a group of individual specimens drawn from an aggregate of such specimens.

DEFINITION OF TERMS AND MATHEMATICS

Frequency Distributions

The variability pattern can be examined both by graphical and by mathematical means. If the graphical procedure is to be followed and the quality characteristic is measured by the method of variables, the data should first be thrown into the form of a frequency distribution. An illustration of this form of presentation appears in Table 1. It will be observed that the total range of the observations is broken into equal intervals and for each interval the number of observations is tabulated. Graphically this distribution may be shown in various ways and the four illustrated in Figs. 1 to 4 will be found useful. On Fig. 1 the data are shown in the form of a histogram. This type of chart presents the most complete picture of the distribution. The width of the columns expresses the *class interval* while the height indicates the number of observations falling within the range of the class interval. Figure 2 illustrates a simpler form of presentation, the *frequency polygon*, and is constructed by omitting

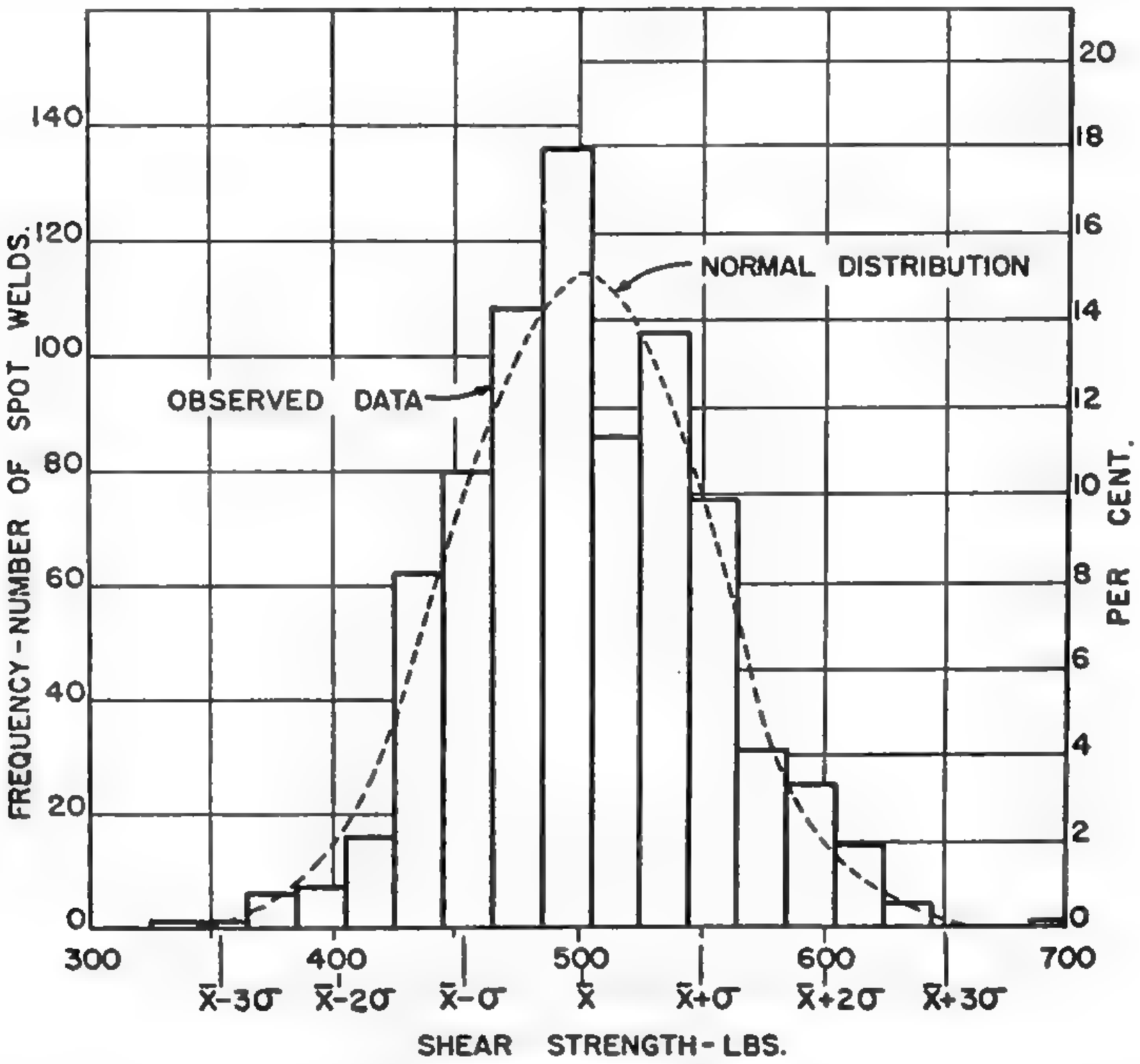


Fig. 1.—Histogram, Data from Table 1

the separate columns of Fig. 1 and merely connecting the mid-points of the tops of the columns. This method of presentation facilitates the plotting of several distributions on one chart for comparison. The cumulative distribution of Fig. 3 is known as an *ogive* and is constructed by plotting the cumulated frequency (or cumulated percent of total frequency) at the upper limit of each class interval.

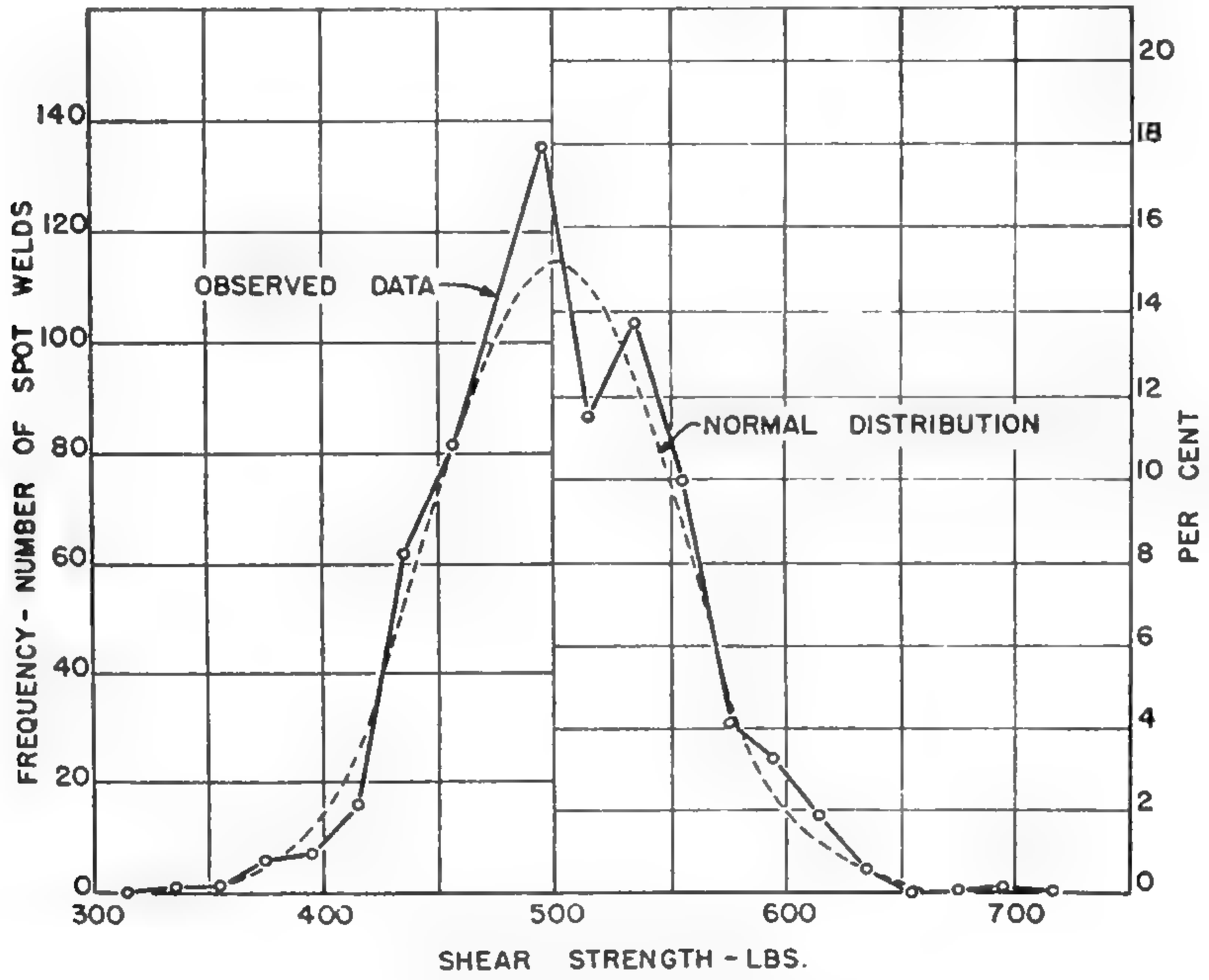


Fig. 2.—Frequency Polygon, Data from Table 1

A point on a curve of this form is to be read as the total number or percent of welds from the vertical scale having a strength less than the corresponding value on the horizontal scale. One advantage of this form is that the selection of the class interval size is less critical in the determination of the shape of the curve than is the case with the frequency polygon. If it is otherwise desirable class intervals may be selected so as to have varying widths. The ogive will also facilitate the comparison of the number of items at the extremes of different distributions.

The selection of the class interval to use in constructing the frequency distribution requires some care but it is not possible to set up completely objective rules. If the readings from which the data are compiled are substantially continuous, the selection of the class interval boundaries will be determined mainly by the number of classes desired. If, however, there is any considerable discontinuity (as, for instance if the data of Table 1 had been recorded only to the nearest even multiple of 10 lb.) the boundaries of the class intervals should have been located halfway between the closest of two possible recorded values. If as in Table 1 intervals of 20 lb. are used the boundaries would then have to be at 325, 345, 365, etc., pounds. The rule may be stated that when there are points at which readings cluster, the class intervals should be planned so that the points of cluster are symmetrically distributed within each class about its mid-point. Provided that there are no points of cluster, a preliminary analysis may be made by selecting an interval which will be convenient for tabulation and which will give a total of from 15 to 25 classes. It will then be necessary to experiment with different intervals until the desired result is obtained. During this process the following rules should be kept in mind:

Small intervals tend to bring about irregularities in the contour of the dis-

tribution. These irregularities may be the result of chance factors and have no real significance.

Large intervals lead to a smoothness which may cover up irregularities of a significant character.

A study of a frequency distribution such as the one illustrated in Table 1 should have for its purpose either of the following objectives: a comparison with an objective standard or mathematical model, or a comparison with one or more other empirical distributions so as to assist in the isolation of causes of similarity or difference.

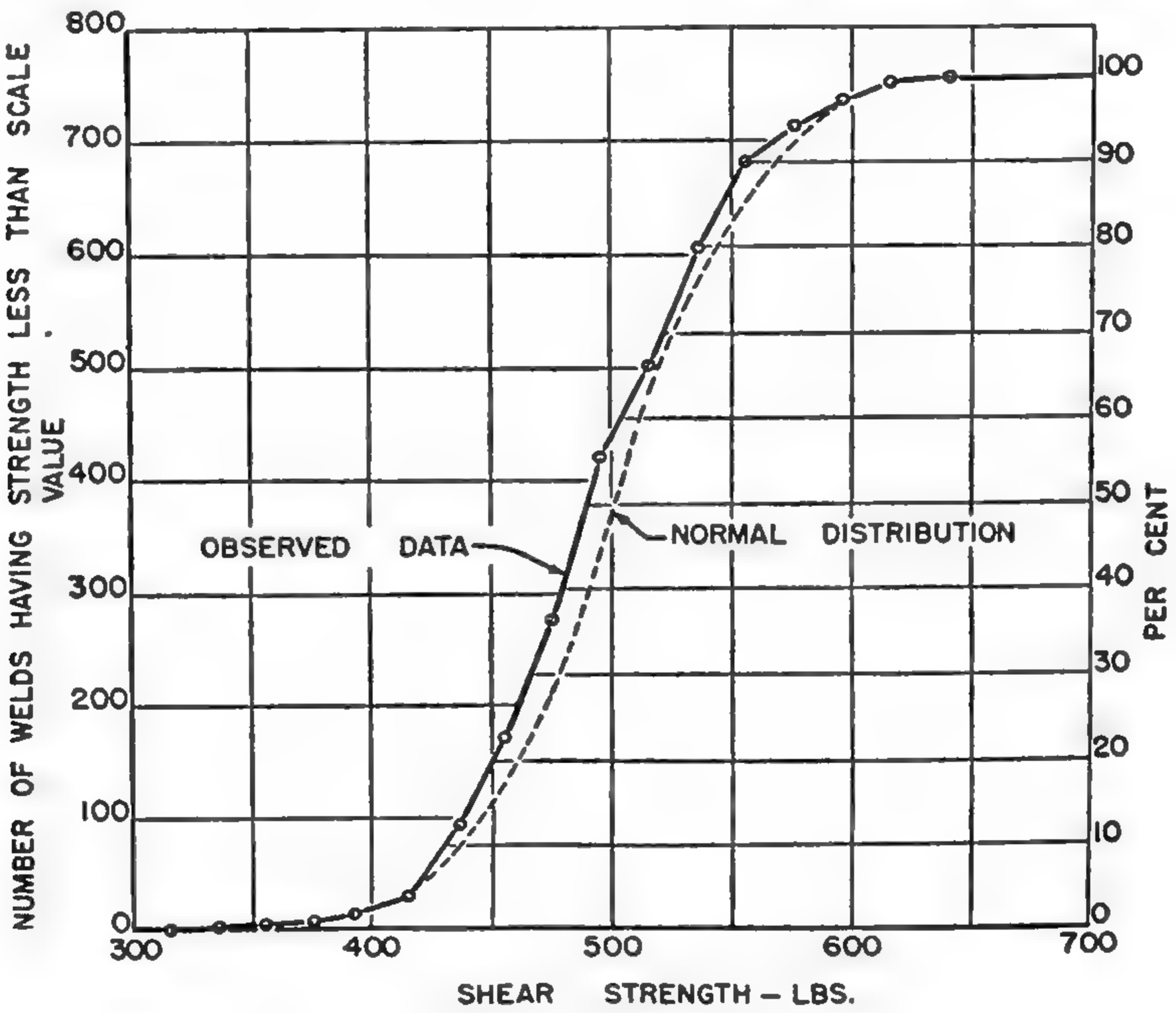


Fig. 3.—Ogive, Cumulative Distribution
Data from Table 1

Mathematical Analysis

In order to facilitate a quantitative comparison among distributions a number of mathematical measures have been devised to describe the important characteristics of a set of measurements. These measures may usually be computed either from the original data or from the frequency distribution. If the sample is small it is better to calculate the measures from the ungrouped data. If, however, the data are made up of a large number of items, particularly if the data have already been grouped into a frequency distribution, it will be simpler to compute the descriptive measures from the distribution itself.

Basic Symbols

$X_1, X_2, X_3, \ldots X_n$ = any set of n observed values.

ΣX = the algebraic sum $X_1 + X_2 + X_3 + \ldots + X_n$.

n = number of observed values.
= number of values falling into a single class interval in a frequency distribution.

X_m = the mid-point value of a class interval.
= the width of a class interval.

Measures of Central Tendency.—A measure of central tendency is a single quantity which is chosen to give the best representation of the data as a whole. The most commonly used measure for this purpose is the *arithmetic mean* or *average* which will be referred to hereafter simply as the *mean*. The mean, $\bar{X}$, can be defined in terms of the data as follows:

$$\bar{X} = \frac{X_1 + X_2 + X_3 + \ldots X_n}{n} = \frac{\Sigma X}{n} \quad (1)$$

If the values are large some reduction in computation time may be realized by

selecting some arbitrary point near the middle of the range and measuring the deviations first from this point. If the arbitrary point is indicated as X' each deviation will be $X-X'$. The mean may then be calculated precisely as follows:

$$\bar{X} = X' + \frac{\Sigma(X - X')}{n} \qquad (2)$$

If the data are in the form of a frequency distribution the mean may be calculated:

$$\bar{X} = \frac{\Sigma(f \cdot X_m)}{n} \qquad (3)$$

where X_m is most conveniently chosen as the mid-point of class interval.

If an arbitrary mean is employed

$$\bar{X} = X' + \frac{\Sigma f(X_m - X')}{n} \qquad (4)$$

Since the class intervals are usually of equal width, it is possible to simplify the calculations still further by expressing each deviation from X' in terms of class interval units. Formula 4 can be rewritten

$$\bar{X} = X' + \left(\frac{\Sigma fd}{n}\right) i \qquad (5)$$

where $d = (X_m - X')/i$ and i = the value of the class interval. This procedure is clarified by the example in Table 1. The arbitrary mean X' is selected as 514.5 lb. at the mid-point of the class interval. The class interval i is 20 pounds. The column headed fd gives the approximate total deviation of all items in their respective classes by treating the items in each class as if they had the single value of the mid-point of the class. The total of this column will give the value Σfd in class interval units necessary for substitution in formula 5.

Other Measures of Central Tendency.—The *median* is the value which, when located on the arrangement of items in order of magnitude, will leave an equal number on either side.

The *mode* is the most typical value and may be found as the highest point on a smooth distribution curve. The mode may be a more significant measure of central tendency than the mean in representing an unsymmetrical distribution. On the other hand, both the median and the mode have the disadvantage of not being related mathematically to the quantitative values of the original data.

Measures of Dispersion. A measure of dispersion of a frequency distribution is a measure of the scatter of the individual items forming the frequency distribution. Since the scatter will determine the proportion of values which will lie outside the tolerance limits or the closeness to which such limits are approached, the measure of such scatter becomes very important.

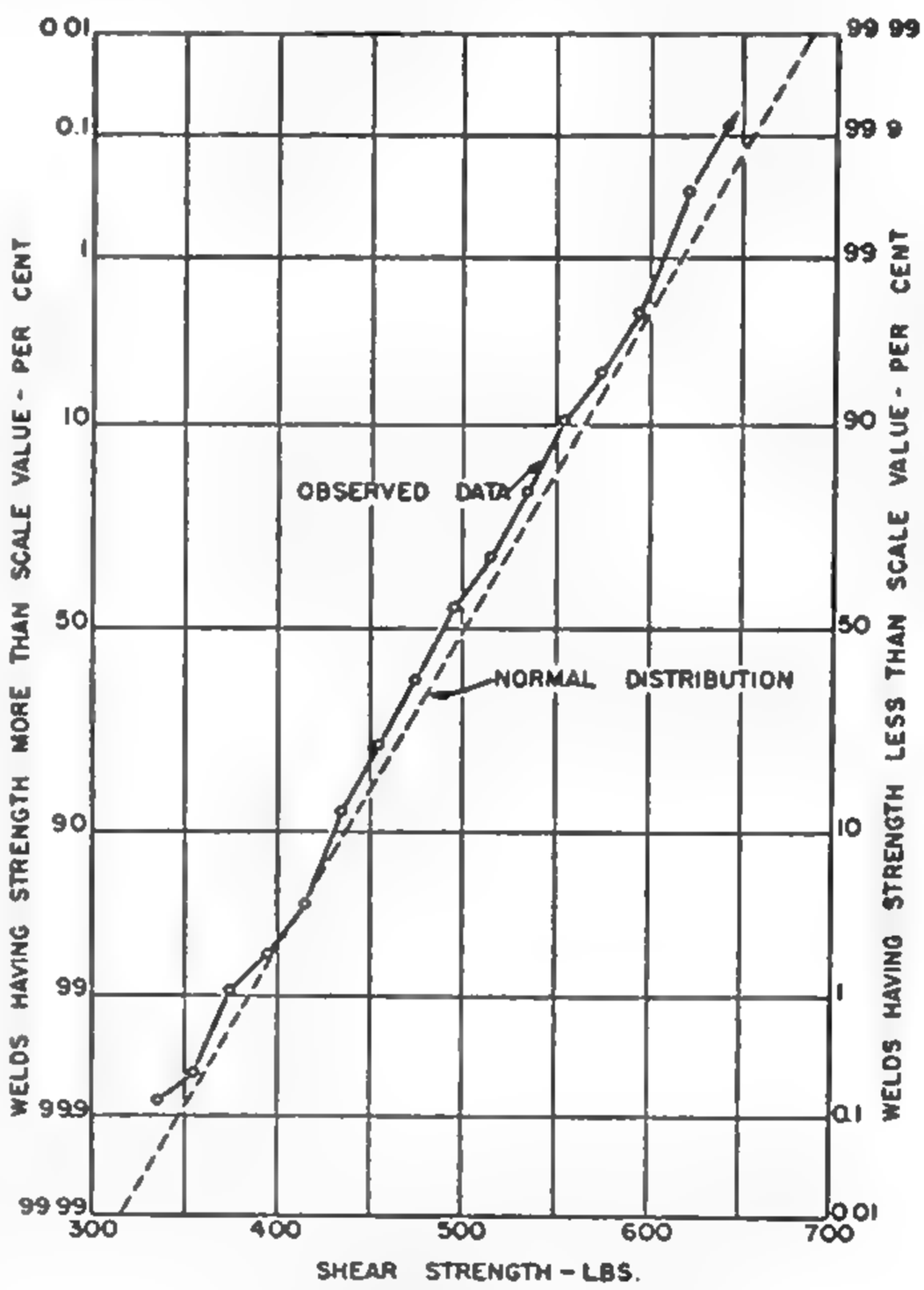


Fig. 4.—Ogive, Cumulative Distribution on Probability Paper
Data from Table 1

The *range* is the difference between the extreme values. This measure is simple to compute but it has the disadvantage of being influenced by the erratic values found at the ends of a distribution. In Table 1, for example, there is a single value in the highest class interval which must have a value at least 40 lb. higher than the next lower value. If this specimen had been omitted the range would have been changed considerably although values of all the other 756 items remained the same. The range therefore cannot be considered as being actually descriptive of *all* the data, though it may be applicable to small samples.

The *average deviation* is a measure of dispersion which avoids the weakness of

the range by employing all the data in its computation.

$$\text{(Average Deviation) } AD = \frac{\Sigma|X - \bar{X}|}{n} \tag{6}$$

The numerator expresses the sum of all the deviations of the items from their mean with all signs considered as positive.

This measure of dispersion is easily understood and enables the dispersion of a number of lots of data to be compared on a quantitative basis. However, neglect of the signs limits the value of the average deviation in mathematical applications.

The *standard deviation* as a measure of dispersion avoids the disadvantages of the average deviation by the process of squaring all the separate deviations.

$$\text{(Standard Deviation) } \sigma = \sqrt{\frac{\Sigma(X - \bar{X})^2}{n}} \tag{7}$$

It will be seen that the standard deviation is the root-mean-square (rms.) of all the deviations of the items from their mean.

The computation of the standard deviation can be simplified by selecting some point other than the mean and first calculating the average squared deviation from this selected point as was done in computing $\bar{X}$. The formula for the standard deviation then becomes:

$$\sigma = \sqrt{\frac{\Sigma(X - X')^2}{n} - (X' - \bar{X})^2} \tag{8}$$

If the arbitrary point X' is taken as zero so that the squares of the deviations become the squares of the actual recorded values the above formula becomes:

$$\sigma = \sqrt{\frac{\Sigma X^2}{n} - \bar{X}^2} \tag{9}$$

Of the above formulas (9) is particularly applicable to the use of computing machines while (8) will involve smaller numbers so as to be useful when a computing machine is not available.

If the standard deviation is to be computed from data in the form of a frequency distribution, formulas 7, 8 and 9 can be rewritten, respectively:

$$\sigma = \sqrt{\frac{\Sigma f(X_m - \bar{X})^2}{n}} \tag{10}$$

$$\sigma = \sqrt{\frac{\Sigma f(X_m - X')^2}{n} - (X' - \bar{X})^2} \tag{11}$$

$$\sigma = \sqrt{\frac{\Sigma f X_m^2}{n} - \bar{X}^2} \tag{12}$$

It is possible to simplify the computations when all class intervals are of equal width by using the same method as was employed in the computation of the mean. The root-mean-square deviation is first computed in units of class intervals and then multiplied by the class interval length to bring the answer into the units of the original data. Formula 11 can be rewritten in terms of d and i as follows:

$$\sigma = i\sqrt{\frac{\Sigma f d^2}{n} - \left(\frac{\Sigma f d}{n}\right)^2} \tag{13}$$

This method is illustrated at the bottom of Table 1.

The term *variance* is applied to the square of the standard deviation.

A useful measure of dispersion is the *coefficient of variation*. This merely expresses the standard deviation as a percent of the mean as indicated by the formula:

$$C_v = \frac{\sigma}{\bar{X}} 100 \tag{14}$$

The coefficient of variation may be applied to the establishment of standards of variability of product when the variability can be considered as varying approximately in proportion to the mean. If, for example, samples of spot welds show that the coefficient of variation remains constant over a considerable range of thickness of the parts welded, it will be possible to estimate the standard deviation in any case when the mean is known. When used to describe a process the term *consistency* has been applied to the coefficient of variation.

Skewness.—The term *skewed* is applied to a frequency distribution in which the area under the curve on one side of the peak is greater than on the other, and the curve is said to be skewed in the direction of the greater area. Under conditions of skewness it will be found that the mean will be moved away from the mode in the direction of the skewness and the median will be moved in the same direction but to a less amount. Mathematical measures may be used to evaluate skewness quantitatively and are given in most texts on statistical methods.

The Normal Curve

The general shape of the distribution in Fig. 1 is frequently found to be characteristic of the distribution of measures of quality found in lots of product produced under controlled conditions. It is possible to approximate this form by a mathematical curve called the *normal* or *Gaussian curve.* A normal curve has been fitted to the data of Table 1 in Figs. 1 to 4. This fitted curve has the same parameters (mean and standard deviation) as the original data. One great advantage of this curve is that only these two parameters are necessary to describe the curve completely. It is therefore possible to construct a table that will show the proportion of items in a normal distribution which lie between the mean and any distance from the mean expressed in units of standard deviations. If the mean and standard deviations are known for a lot of data which follows the normal curve it will be possible to refer to the table and ascertain how many items will fall within any assigned range. This table of normal curve areas can be found in many sources* and a sample of values is shown below:

Limits	Percent of Total Area
$\bar{X} \pm 0.6745\sigma$[a]	50.00
$\bar{X} \pm 1\sigma$	68.26
$\bar{X} \pm 2\sigma$	95.46
$\bar{X} \pm 3\sigma$	99.73
$\bar{X} \pm \infty$	100.00

[a] As used in this chapter the symbol $\pm$ means the included range, i.e., $\bar{X} - 0.6745\sigma$ to $\bar{X} + 0.6745\sigma$.

The first limit above gives the range known as the *Probable Error.* At the extreme limits nearly all the curve falls in a range of three standard deviations on either side of the mean.

Before using the table of the normal curve it is necessary to be certain that the normal form is applicable to the data under investigation, but it is often possible to check this agreement by reference to other observations obtained under similar conditions. In any particular case the agreement with the normal curve can be examined most easily by plotting the ogive on probability paper as shown on Fig. 4. On this type of graph paper the ordinate scale is so designed that the ogive of the normal distribution becomes a straight line. The agreement of the particular ogive with a straight line will therefore indicate the validity of the assumption that the distribution is normal in form.

When a distribution departs from the normal form while at the same time other evidence points to the fact that the normal form is to be expected, the discrepancy may throw light upon factors affecting the process under investigation.

If the distribution is flat on top with no definite mode or if there is more than one peak, it is probable that the process is not under control so that in effect the distribution is made up of several separate distributions each with its own mode. The distribution of Fig. 1 shows this lack of control. It appears that during part of the process period from which the samples were taken the mode was at about 500 lb. but that during another period the quality was better with a mode at 530 pounds. If there is a slow shifting about of the process, the top of the distribution may merely be flattened out so as to obscure any particular modal tendency.

If the distribution under examination has been screened by a previous inspection there will be evidence in the form of an abrupt cutoff at one or both ends of the curve.

The distribution may be fairly smooth but show skewness or lack of symmetry. This characteristic may be the result of lack of control when no additional peaks are produced. It may also result from the fact that the quality measured is not affected in direct proportion by the factor which is actually controlled in the process. An example may be found in the case of electrical capacitors. A particular lot measured as to capacity showed a pronounced skewness because of variations in thickness of the dielectric. Samples of dielectric used showed a normal distribution but since the capacity varied inversely with the thickness of the dielectric, the capacity distribution was skewed.

In order to study the shape of a distribution curve as has been described it is necessary to have a rather large number of items in the sample since otherwise chance effects will lead to irregularities in the shape of the curve which have no actual significance. The determination in any particular case of the significance of variations in shape between two distributions

* See Bibliography at end of chapter.

can be examined by means of the Chi-square test.*

Standard Error of the Mean

Just as the shape of the distribution of a sample may vary by chance from the shape of the distribution from which the sample was taken and also from other samples from the same lot, the mean of the sample itself is subject to chance variations. Since the mean is so important in describing a distribution, it is desirable to ascertain in the case of any particular sample just how good the mean is in telling what is the mean of the parent lot. The formula for the standard deviation of the means of successive samples is:

$$\sigma_{\bar{x}} = \frac{\sigma'}{\sqrt{n}} \qquad (15)$$

where σ' is the standard deviation of the lot from which the samples are taken and n is the size of the sample. The symbol $\sigma_{\bar{x}}$ is known as the *standard error of the mean*. The frequency distribution of sample means will be normal in form and therefore it will be possible to refer to a table of normal curve areas and estimate the proportion of sample means which will deviate by more than any assigned amount from the lot mean.

If the standard deviation of the lot is unknown but is estimated from the single sample, the following limitations must be recognized:

(1) The standard deviation of the sample tends, on the average, to be less than the standard deviation of the lot from which it was taken. This may be allowed for by use of the formula

$$\hat{\sigma} = \sigma_s \sqrt{\frac{n}{n-1}} \qquad (16)$$

where $\hat{\sigma}$ is the best estimate of the standard deviation of the lot to be made from the sample standard deviation, σ_s is the observed standard deviation of the sample and n is the size of the sample. The standard error of sampling may be calculated by combining the preceding two formulas (15 and 16) as follows:

$$\sigma_{\bar{x}} = \frac{\sigma_s}{\sqrt{n-1}} \quad \text{or} \quad \frac{\hat{\sigma}}{\sqrt{n}} \qquad (17)$$

(2) When the sample is small (less than 30) the substitution of the standard deviation of the sample for the standard deviation of the lot, even though an adjustment is made to allow for the bias due to size, will involve the substitution of a value which may be quite different from the actual standard deviation of the lot. If the standard deviation of the lot is estimated from a single small sample the normal curve of areas should not be used to estimate the probable agreement between sample mean and lot mean. *Student's t Test* should be applied and in place of the normal area table the table for t should be used. An adaptation of this table for determining the reliability of single sample means may be found in various texts.*

The Binomial Distribution

So far the data considered for analysis have been of the type which could be considered as essentially continuous. In many situations, such as in acceptance sampling, the quality data may be of a different character and will be expressed in terms of the fraction of a lot which is defective. The probability of obtaining a random sample with a certain fraction defective from a lot which has a particular proportion defective may be calculated as follows:

If a sample of n pieces is taken at random from a lot in which p is the fraction defective and q is the fraction good so that $p = 1 - q$, the probability of finding in the sample 0 to n defective pieces will be as follows:

Number of Defectives in Sample	Probability of Occurrence
0	$(q)^n$
1	$(p)(q)^{n-1}n$
2	$(p)^2(q)^{n-2}\frac{n(n-1)}{2\cdot 1}$
3	$(p)^3(q)^{n-3}\frac{n(n-1)(n-2)}{3\cdot 2\cdot 1}$
r	$(p)^r(q)^{n-r}\frac{n(n-1)(n-2)\ldots(n-r+1)}{r!}$

(18)

The sampling distribution obtained as described above is called the binomial distribution because the various probabilities of occurrence of from 0 to n defectives in a sample of size n are obtained from the terms of the expansion of the binomial $(q+p)^n$.

Figure 5 shows the form of the distribution of two binomials for fraction defective. (The curve could have been drawn

* See Reference 7 in bibliography or any standard text.

for *number of defectives* instead of *fraction defectives*.) The proportion of defectives in the lot from which the samples are taken is the same for both curves, $p = 0.10$. The difference lies in the sizes of the sample. One curve gives the probabilities for samples of 20 each, the other for samples of 100 each. It will be observed that the first curve is skewed toward the right while the other is nearly symmetrical. A comparison between the second curve and the normal curve in Fig. 1 will show a close resemblance. The case, a table of normal curve areas can be used in the prediction of the probabilities for samples. The normal curve can be considered as a satisfactory approximation to the binomial if the product pn is greater than 4.

In quality control problems it is frequently required to find the probability of occurrence of a random sample with more than a certain proportion of defectives. This problem may be solved by summing the separate probabilities given by the terms of the binomial ex-

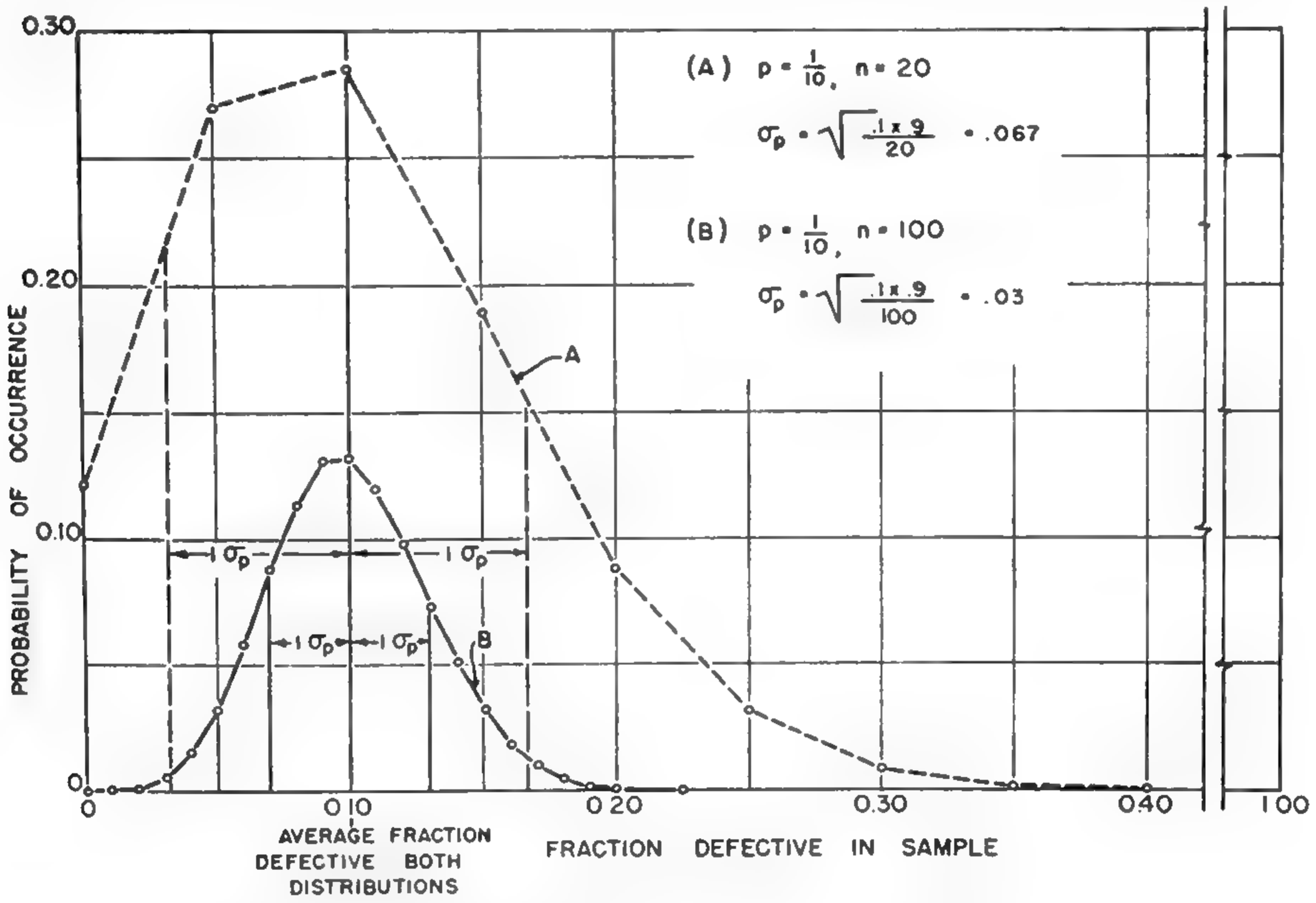


Fig. 5.—Binomial Distribution for $p = 0.10$, $n = 20$ and $n = 100$

expected relationship between the normal and the binomial distributions may be summarized as follows:

(1) If $p = q = 0.50$ the binomial will be symmetrical and will approach the normal in form as n becomes larger.

(2) If $p \neq q \neq 0.50$ the binomial will be skewed but as n becomes larger this skewness will become less. Therefore as n becomes large the departure of the binomial from the normal form will be slight so that an assumption of normality may be considered satisfactory for most purposes.

Conditions (1) and (2) may be combined into a single condition which can be applied to test whether in a particular

pansion and subtracting the result from 1.00. For instance, suppose a lot has 10% defective and it is required to find the probability that a sample of 60 will have more than 10 defectives in it. The probabilities of obtaining all the separate number of defects from 0 to 10 can be calculated. The sum of these fractions subtracted from 1 will give the probability of the sample having more than 10 defectives. The solution in this manner is very laborious, and if it can be assumed that the distribution of the number of defectives in samples of 60 will be normal or nearly so a much easier method of solution can be employed Since in this case pn is equal to 6 the

assumption of normality may be made. The standard deviation of a binomial distribution is given by the formula:

$$\sigma_c = \sqrt{pqn} \qquad (19)$$

where σ_c is the standard deviation of the number of defectives in successive samples:

For the above example the standard deviation is calculated as follows:

$$\sigma_c = \sqrt{\left(\frac{1}{10}\right)\left(\frac{9}{10}\right)60} = 2.3$$

The numerical value of the probability of finding more than 10 defects in a random sample is represented by a portion of the area under the curve of the binomial distribution for *number of defects*. Since the area under the entire distribution is equal to 1 and represents the sum of the probabilities of finding 0 to 60 defects, the area between 10.5 and 60 represents the probability of finding more than 10 defects. Because $pn = 6$, the binomial curve can be closely approximated with the normal curve and the area in question can be solved by referring to a table of normal curve areas. This is done by expressing the limits of the area in standard deviation units as follows:

$$\frac{10.5 - 6.0}{2.3} = 1.96 \text{ standard deviations}$$

where 6.0 represents the average number of defects per sample of 60 ($p = 10\%$).* From the table of normal curve areas it will be found that approximately 2.5% of the curve lies beyond 1.96 standard deviations above the mean and it can be concluded that 2.5% of the samples of 60 will have more than 10 defectives.

If the conditions of the problem had been such that pn had been less than 4 the solution would have been a poorer approximation with an error in the direction of underestimating the proportion of samples above the limit when this limit is above the mean. If the limit is below the mean the error will be in the opposite direction.

* Since the normal curve is symmetrical about the average, proportional parts of the normal probability curve can be found in a table of areas for values of the half of the curve included by the average and the ordinate in question, i.e., the area bound by the average and $+\infty = 0.50$. To find the total area in question it is necessary to add the area bound by the average and $-\infty = 0.50$ and the area bound by the average and $+1.96\,\sigma = 0.475$ from a table of areas. The sum = 0.975 represents the probability of finding *less* than 10 defects. This value subtracted from 1.000 equals 0.025.

The Poisson Distribution

A large proportion of the problems in quality control involve the consideration of situations in which p, the fraction defective, is quite small. Under such conditions a modification of the binomial distribution may be used in a form which is considerably easier to handle. This distribution is called the *Poisson Distribution* and is the limiting form of any binomial as p becomes smaller and n becomes larger so that pn remains constant. The probability of the occurrence of varying number of defectives in random samples can be computed as follows:

Number of Defectives	Probability of Occurrence
0	e^{-np}
1	npe^{-np}
2	$\frac{(np)^2}{2}e^{-np}$
r	$\frac{(np)^r}{r!}e^{-np}$ (20

The symbol e is the constant 2.718, the base of the natural logarithms.

It will be apparent that the terms of the Poisson distribution are easier to compute than the corresponding terms of the binomial distribution. It is also apparent that there is only one parameter needed to determine a particular distribution, namely, $pn = \bar{c}$, the average number of defectives in all the samples. It is therefore possible to construct a simple chart which will indicate the maximum number of defectives to be expected for various values of pn. An example of such a chart is illustrated in Fig. 6. Tables have been computed which will give the summation for the terms of the Poisson distribution for varying values of pn so that any problem involving the determination of probabilities under the Poisson distribution can be solved with the minimum of labor.

The standard deviation of the Poisson distribution is given by the formula

$$\sigma_c = \sqrt{pn} \qquad (21)$$

This expression may be derived from the corresponding formula (19) for the binomial distribution $\sigma_c = \sqrt{pqn}$. If p is very small, q will be nearly equal to 1 and can be neglected.

In quality control work the Poisson distribution has two important applications:

(1) It makes possible the use of a single chart for the setting of sampling limits and thus avoids the use of formulas.

(2) It permits the setting of sampling limits for a number of defects when both p and n are unknown provided n is large and pn is known. Such a situation arises in the control of the number of cracks in a fixed length of material. The sample is this fixed length and cannot be expressed in terms of n. The average number of cracks in the fixed length can be measured and will be found to be equal to pn.

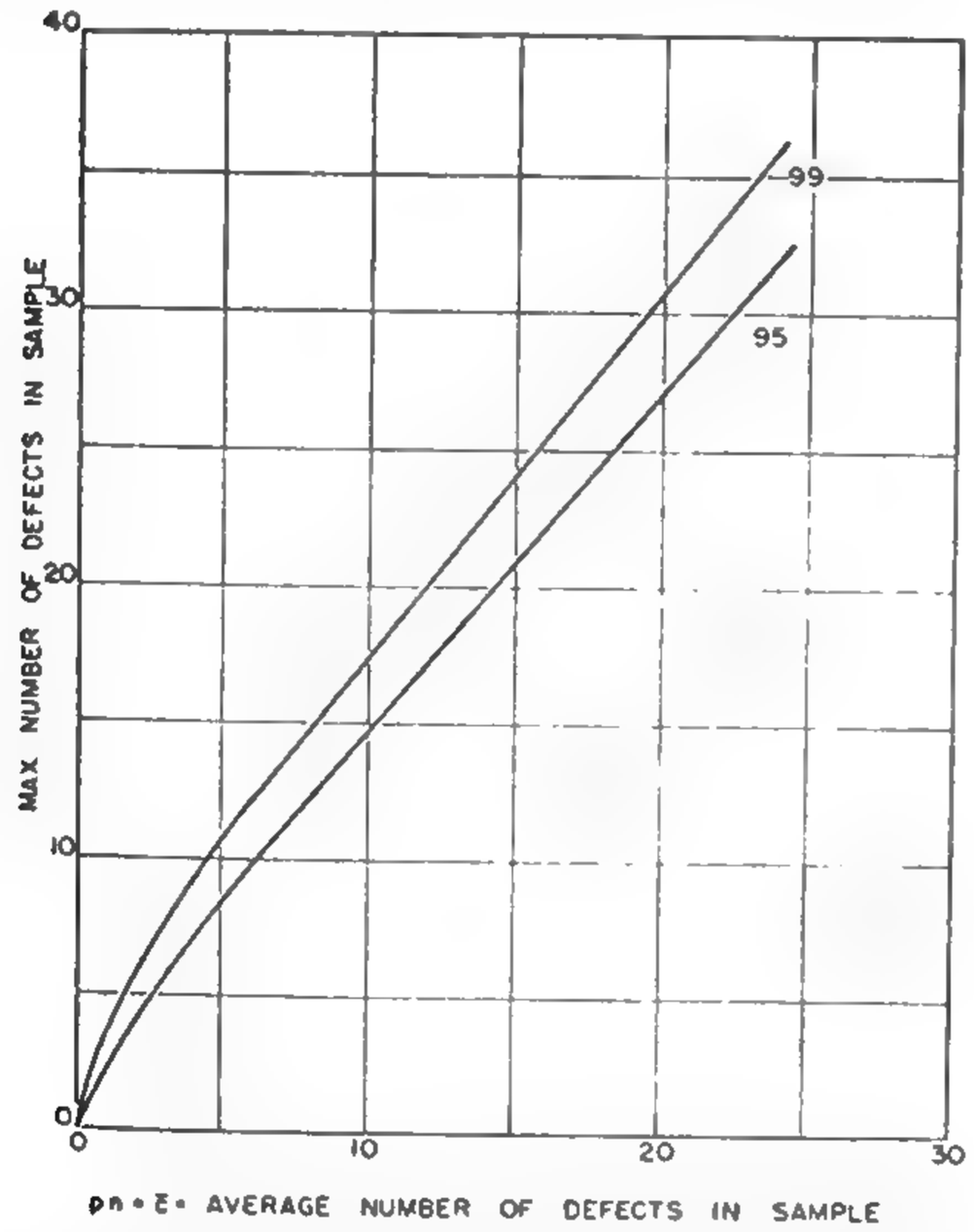


Fig. 6.—Use of the Poisson Distribution to Determine the Maximum Number of Defects Expected in a Random Sample from a Given Lot for Probabilities of 95 and 99%

STATISTICAL TESTING PROCEDURE

Elimination of Sampling Bias

Mathematical analysis of statistical data always assumes that the sample is completely random. That is, *every specimen in the entire lot has an equal chance of being selected*. The physical model for such a purely random sample is chips selected from a bowl. Each chip has a number which marks that chip as a component of the universe represented by the totality of the chips in the bowl. The chips are thoroughly mixed and samples of n chips are withdrawn and recorded. The sample is replaced in the bowl, remixed and a second sample is selected. In this idealized experiment, samples are actually drawn from a constant universe under essentially the same conditions and are effectively random. The engineer attempts to approach the bowl experiment by controlling his process and method of sampling. A more thorough treatment of the subject of random sampling is beyond the scope of this chapter. Usually the engineer's knowledge of the process and his inspectors will determine the procedure for best approaching randomness.*

The product of each producing unit should be properly represented in any sample or series of samples from which an inference is to be drawn. This obvious requirement is so often overlooked that it bears emphasis.

Even though the engineer has gone to considerable trouble to insure that the specimens were selected in as random a manner as possible, he has no assurance that he was selecting specimens, in effect, from a single bowl universe. In other words, not only must the samples be randomly selected but they must have been made under essentially the same conditions. Suppose an observer is selecting a series of chips from a bowl and from the samples of chips selected he attempts to draw an inference regarding the quality of the bowl universe. Suppose further that unknown to the observer, someone suddenly during the selection substitutes another bowl of chips whose parameters (average, standard deviation) are significantly different from the first bowl. Obviously, any estimates regarding the first bowl made from samples drawn from both bowls will be in error. The samples were not drawn from a statistically uniform causal system and the data are said to contain assignable causes of variation which in this case was the sudden bowl substitution. Unless the data are statistically uniform a reliable estimate of the lot from the sample cannot be made. There is a statistical test for determining the existence of assignable causes of variation and which assists in deciding

* A simple method for drawing a random sample from a large lot where there is no knowledge of the order of manufacture is to assign consecutive numbers to each specimen. From a table of random numbers arbitrarily select consecutive listings and determine the sample from the specimens with the corresponding numbers.

that predictions are being made from a controlled and homogeneous system. The test is made by applying the sampling results to a *control chart* (described in detail on page 1032). If the control chart indicates lack of control, no reason exists for believing that the specimens are part of a single universe and estimates of the quality of the product will be open to question.

Sampling Inspection Plans

Whenever it is more economical to tolerate the possibility of a small portion of defects finding their way into a process than to inspect 100%* or where the test method is destructive, the specification will usually indicate sampling a portion of a lot or a periodic portion of a continuous production.

It is axiomatic that any plan which does not provide for 100% inspection may lead to a wrong decision. If inspection is non-destructive and the economic or functional requirements are such that defects are inadmissible, 100% or tandem (repeated) inspection must be used. When the test method is destructive the nearest approach to complete inspection is *drastic testing* (see page 1038).

If it were true that when a sample is inspected and found to be of quality Q, one could immediately and correctly infer that the quality of the lot was also Q, there would be no sampling problem. It can be shown, however, based on the laws of mathematical probability, that the fraction defective of small samples taken from a large lot of fairly good quality will be less than the true fraction defective of the parent lot more often than it will be greater. The relationship between the results of the sample, and the parent lot is a function of the sample size, the lot quality and the tolerated risk of error.

Statistical Methods for Determining Sample Size.—When first initiating a test program, whether this be for purposes of inspection or of investigation, few or no data are available regarding precision and no precise determination of the proper sample size is possible. Since uncontrolled guessing on this point so frequently leads to wasted effort, either in the collection of results which later prove to have no significance, or in making an excessive number of tests, it is necessary to have some method of estimating the proper sample size before data are available. One such estimate can conveniently be made in terms of the binomial distribution (see page 1018). This estimate is particularly applicable to simple yes-no attributes, such as the proportion of welds which break in a bend test, but can be extended to many related problems.

It has been shown for the binomial distribution that the standard deviation of the number of defectives c is:

$$\sigma_c = \sqrt{pqn}$$

A reasonable guess for the value of the maximum proportion defective, p, can usually be made from general experience with the material or past records, or from the first few preliminary tests. The desired control statistic, standard deviation of the *fraction defective*, then becomes:

$$\sigma_p = \frac{\sigma_c}{n} = \frac{\sqrt{pqn}}{n} = \sqrt{\frac{pq}{n}} \qquad (22)$$

or:

$$n = \frac{pq}{\sigma_p^2} \qquad (22a)$$

If σ_p is now set at some suitable value, i.e., 1%, a reasonable sample size, n, is easily estimated in terms of the presumed values of p and of q ($q = 1-p$).

The binomial formula (22a) leads directly to a handy reference table first published by T. H. Brown of Harvard University. A modification of this is shown as Table 2. This table shows the number of pieces which must be included in the sample, as a function of the precision as a *percentage of the whole*, when each piece is tested only for a simple attribute, such as good or bad. It thus applies specifically to problems such as good and bad spot welds, the proportion of people who intend to vote for a presidential candidate, and other *single choices*. It must again be strongly emphasized that the number of pieces in the sample tested is entirely independent of the number actually made, or the *size of the population*, provided only that all minor groups are proportionally represented.

Table 2 may be extended, with little error, to the estimation of sample size when there is more than a *single* choice. Thus several sections of a test length of arc weld might be examined for cracks,

* 100% inspection assumes 100% inspection efficiency; practical experience shows that this is seldom achieved

Table 2—Size of Sample for Accuracy Within Prescribed Limits—for Testing by Attributes by Binomial Distribution

$$\sigma_p = \sqrt{\frac{pq}{n}} \quad \text{or} \quad n = pq/\sigma_p^2$$

Values of n = number of pieces in sample when results divide according to percentage ratio indicated:

Total Range of Error $\pm(3\sigma_p)$, %	Std. Dev., σ_p, %	99/1	95/5	90/10	80/20	70/30	60/40	50/50
±0.1	0.03	89 × 10³	428 × 10³	811 × 10³	1.44 × 10⁶	1.89 × 10⁶	2.16 × 10⁶	2.25 × 10⁶
0.3	0.1	9900	48 × 10³	90 × 10³	160 × 10³	210 × 10³	240 × 10³	250 × 10³
0.5	0.17	3565	17 × 10³	32 × 10³	58 × 10³	76 × 10³	86 × 10³	90 × 10³
1.0	0.33	891	4275	8100	14,400	18,900	21,600	22,500
2.0	0.67	223	1069	2025	3,600	4,725	5,400	5,625
3.0	1.0	99[a]	475	900	1,600	2,100	2,400	2,500[b]
4.0	1.3	56	268	506	900	1,181	1,350	1,406
5.0	1.7	36	171	324	576	756	864	900[c]
6.0	2.0	25	119	225	400	525	600	625
8.0	2.7	14	67	127	225	295	338	352
10.0	3.3	9	43	81	144	189	216	225
15.0	5.0	4	19[a]	36	64	84	96	100[d]
20.0	6.7	3	11	21	36	47	54	56
30.0	10.0	1	5	9[a]	16	21	24	25
40.0	13.3	....	3	5	9	12	14	14
50.0	16.7	....	2	4	6	8	9	9

[a] These samples give a $C_{v(p)} > 100\%$ and are meaningless.
[b] Approximate sample sizes commonly used by "Opinion" polls.
[c] Sample size usually considered suitable for engineering research and investigation.
[d] Sample sizes giving a standard deviation of the average amounting to 5% or more of the total range should be regarded as unsuitable for purposes other than the most perfunctory inspections.

and the length thus rated good–fair–bad, or perhaps four-tenths bad. In such cases increase in choice is equivalent to more samples, so the necessary number of samples may be reduced in proportion, i.e., to half for three classes of the attribute, or to one-ninth for ten classes. It may also be noted that since pn is more than 5 for most of the usable part of the table, the departure from a normal distribution is small and there is little error in applying the same reasoning to those common measurements which, while made on an apparently continuous scale, are actually known by common experience only to place the material in one of a few distinguishable classes. Notch-impact tests, for example, are often of this character. When, however, the test scale is actually a continuous variable, a better estimate of sample size can be determined from a table based on *Student's distribution of t*, for example by working backward in Table II of the ASTM *Manual on Presentation of Data, Supplement A*.

Cases are frequently encountered where c is measurable, but p cannot be determined. For example, the magnetic inspection of arc welds might indicate an average of two cracks per foot of weld length, but the cracks might vary in length, or grow with time, and the idea of the proportion of the weld which did or did not crack could be meaningless. In such an example, the number of places in which a crack might have started is obviously very much larger than the number of cracks, whence q will for all practical purposes equal 1, so that the Poisson distribution will apply. The standard deviation for this distribution has been stated:

$$\sigma_c = \sqrt{pn} = \sqrt{c}$$

where c is the total number of cracks (defects) which have been detected (p and n unknown). The average number of defects in an arbitrary amount (length) of the material will be indicated by $\bar{c}$. It will be found more useful in this case to express the range of error in terms of the *Coefficient of Variation* instead of σ_c where

$$C_{v(\bar{c})} = \frac{\sigma_c}{c} \times 100 = 100\,\frac{\sqrt{c}}{c} = \frac{100}{\sqrt{c}} \quad (23)$$

In other words, C_v is actually the number of standard deviations per unit defect expressed in percent. Thus, if the average number of cracks per unit length of weld is to be determined, with $C_{v(\bar{c})} = 5\%$, (a *probable error* of 3%), it will be necessary to examine sufficient material to find 400 cracks, irrespective of the actual amount of material welded or the length which might need to be examined to find this number of cracks. Similarly, a coefficient of 10% would require finding only 100 cracks, while a coefficient of 1% would set the tremendous task of finding 10,000 cracks, as shown in detail in Table 2A.

Table 2A—Size of Sample for Accuracy Within Prescribed Limits—for Testing by Attributes by Poisson Distribution

$$C_{v(\bar{c})} = \frac{100\sigma_c}{c} = \frac{100}{\sqrt{c}}$$

Total Range of Error, $\pm 3C_{v(\bar{c})}$ %	Coeff. of Var., $C_{v(\bar{c})}$, %	Number Defects, c
	Number of defective pieces, c, to be detected	
±0.1	0.03	9×10^6
0.3	0.1	1×10^6
0.5	0.17	361×10^3
1.0	0.33	90,000
2.0	0.67	19,000
3.0	1.0	10,000
4.0	1.3	5,640
5.0	1.7	3,615
6.0	2.0	2,500
8.0	2.7	1,405
10.0	3.3	900
15.0	5.0	400[a]
20.0	6.7	225
30.0	10.0	100
40.0	13.3	56
50.0	16.7	36

[a] Sample size usually considered suitable for engineering research and investigation.

Table 2A has been constructed in a manner similar to Table 2 to show the number of defective samples to be found when the Poisson distribution applies. In this case the precision is expressed as percentage of the average number of defects, which is a more rigorous condition than percentage of the whole as used in Table 2. To obtain this more rigorous condition from Table 2 it is necessary to enter the table not with σ directly, but on a higher line corresponding to the value of $p\sigma$. This correction may be very important when p is small and the less rigorous condition indicates a small sample size.

Acceptance Sampling Plans.—Statistical analysis with regard to industrial production problems is concerned, very often,

with the question, "Is the product acceptable?" rather than with the actual quantitative value of the product quality. The answer to this question is covered extensively by the subject of *Acceptance Sampling*.

It is a matter of importance to the consumer to know the size and quality of the sample required to insure himself that the submitted product is meeting his specifications. The supplier is concerned with what quality he must submit to the consumer in order to:

Keep the number of lots rejected by the consumer to a minimum.

Keep his manufacturing costs at a minimum.

Keep his own inspection costs at a minimum.

The statistician can specify the most economical sampling plan in order to accomplish a certain objective with a given risk of error, but only after the objective of the plan has been clearly stated as decided by the economic or functional requirements of the process.

Most sampling plans, as a result of inspecting a small sample, recognize two types of risks and attempt to treat these risks in a quantitative manner.

1. The chance of a sample giving a *satisfactory* indication, though coming from an *unsatisfactory* lot. This is the *Consumer's* or *Buyer's Risk*.
2. The chance of a sample giving an *unsatisfactory* indication, though coming from a satisfactory lot. This is called the *Producer's Risk*.

There are two sampling inspection plans developed by Harold F. Dodge and Harry G. Romig of the Bell Telephone Laboratories, which are so simple to use and of such wide application that their use has become universal. These plans are known as *Single and Double Sampling* and aim for maximum protection with a minimum amount of inspection.

Nomenclature Used in Dodge-Romig Sampling Plans

N = number of pieces in the grand lot.
n = number of pieces in sample.
p_t = tolerance fraction defective. This represents the maximum fraction defective the consumer can tolerate in his process or final product.
P_c = Consumer's Risk, the probability of accepting a submitted lot of no better than tolerance quality (risk of the first type).
P_p = Producer's Risk, the probability of rejecting a submitted lot of a least tolerance quality (risk of the second type).
$\bar{p}$ = process average (expected) fraction defective.
c = acceptance number, the maximum allowable number of defective pieces in a sample.
p_L = Average Outgoing Quality Limit (AOQL), maximum value of average fraction defective in product after inspection and replacement of defects.

The Dodge-Romig sampling plans assume inspection of lots of material by the method of attributes where the test is *non-destructive*. The operational procedure for the *Single Sampling* plan is as follows:

(*a*) Inspect a random sample of n pieces.
(*b*) If the number of defects does not exceed the value c, accept the entire lot.
(*c*) If the number of defects exceeds c, inspect the entire lot.
(*d*) Replace all defective pieces with non-defective pieces.

Though in any sampling system, an acceptance number of $c = 0$ will give the smallest sample size, this acceptance number will not necessarily give the most economical sample size due to the amount of detailing (100% inspection) in the long run (step *c*).

The basis for this plan is briefly outlined below, though the explanation is not necessary for the successful use of the construction charts. The average amount of inspection is expressed by the formula

$$I = n + P_p(N - n) \qquad (24)$$

where $P_p(N-n)$ represents the number of pieces which must be detailed. For any sample size and given average fraction defective, there will be a definite probability of obtaining 0, 1, 2, 3, etc., defects.

The sample size can be adjusted so that this probability is a constant (consumer's risk, arbitrarily selected at 0.10 in this plan). If the average lot fraction defective $\bar{p}$ increases, the probability of accepting the lot for a given acceptance number will be less than 10%, and if $\bar{p}$ decreases the probability of accepting will be greater than 10%.

For a given average fraction defective and lot tolerance fraction defective, the above formula can be solved for different acceptance numbers (integers from 0 upward) by the use of the Poisson distribution. There will be one sample size and corresponding acceptance number which will make I a minimum, so long as the process average remains constant. One of the requirements of this inspection plan is the estimate of the process average. Naturally, if the process average were known and there was assurance that it was being continually held at the same level, additional sampling inspection would not be necessary. Such is seldom the case. Although a fairly accurate estimate can be obtained from past records and the control chart, the sampling system guards against sudden poorer than normally expected quality due to unexpected poor lots of raw material, equipment breakdown, and human error. So long as the process average remains fairly constant, the manufacturer is reasonably sure that his inspection costs are being kept at a minimum for the conditions which exist. If the lot quality suddenly deteriorated, the producer would find that his inspection would suddenly increase and approach 100%. This would immediately become an incentive for him to inquire into the cause and improve the quality of his product. One disadvantage of this method of inspection is that unless the *process average* is considerably better than the *lot tolerance average*, most of the lot will have to be detailed. If $\bar{p} = p_t$, 90% of the lot will be detailed. This is the cost one must pay for minimum risk against accepting poorer than specification quality. The smaller the risk, the higher the cost.

Charts for Solving Single Sampling Plan.—Figures 7, 8 and 9 are provided for the solution of the single sampling plan and determining the minimum average amount inspected. Tables are easily constructed from these charts for a given lot tolerance fraction defective and process average and the varying lot sizes which might be met in a particular shop. These charts are all determined for a consumer's risk of 10%. Charts for lot tolerance fraction defective are particularly useful where each lot is identified and earmarked for a specific location or where a customer is purchasing one lot at a time.

Average Outgoing Quality Sampling System.—As $\bar{p}$ increases, the probability of detailing increases. If defects are replaced with non-defective pieces it will be found that $\bar{p}$ plotted against *AOQ* (Average Outgoing Quality) is a peaked curve. The peak of the curve is the *Average Outgoing Quality Limit* (*AOQL*) or the maximum average fraction defective possible for a given sampling system regardless of the process average. Figure 10 provides the solution for the *AOQL*. The *AOQL* is more useful than the lot tolerance fraction defective where lots lose their individual identity and may go any place within a plant or where several small lots are being shipped to a customer as part of a large lot whose *AOQL* is of interest.

It should be noted particularly that the single and double sampling plans may be safely applied whether the process is in statistical control or not. A process which is not in control will be forced to 100% inspection when the quality becomes low. Sampling inspection can be applied during any stage of the manufacturing process. The lot tolerance defective or *AOQL* and the consumer's risk depend on the requirements of the process which include cost of inspection, rework or replacement, and the cost to the manufacturer either in dollars or good will, resulting from defective pieces finding their way to the consumer.

Illustrative Example

A manufacturer makes a welded part which is subject to a non-destructive test such as magnetic inspection. One hundred percent inspection is neither economically possible nor functionally necessary.

Given:
Lot size, $N = 5000$
Specified lot tolerance, $p_t = 5\%$
Process average quality, $\bar{p} = 1.5\%$

Find:
1. Single sample plan which will give minimum amount of inspection.
2. Average amount of inspection required per lot.

Calculations:
Referring to Fig. 7
$\bar{p}/p_t = 0.015/0.05 = 0.3$
$p_t N = 0.05 \times 5000 = 250$
Acceptance number $c = 9$

Referring to Fig. 8
$p_t N = 250$

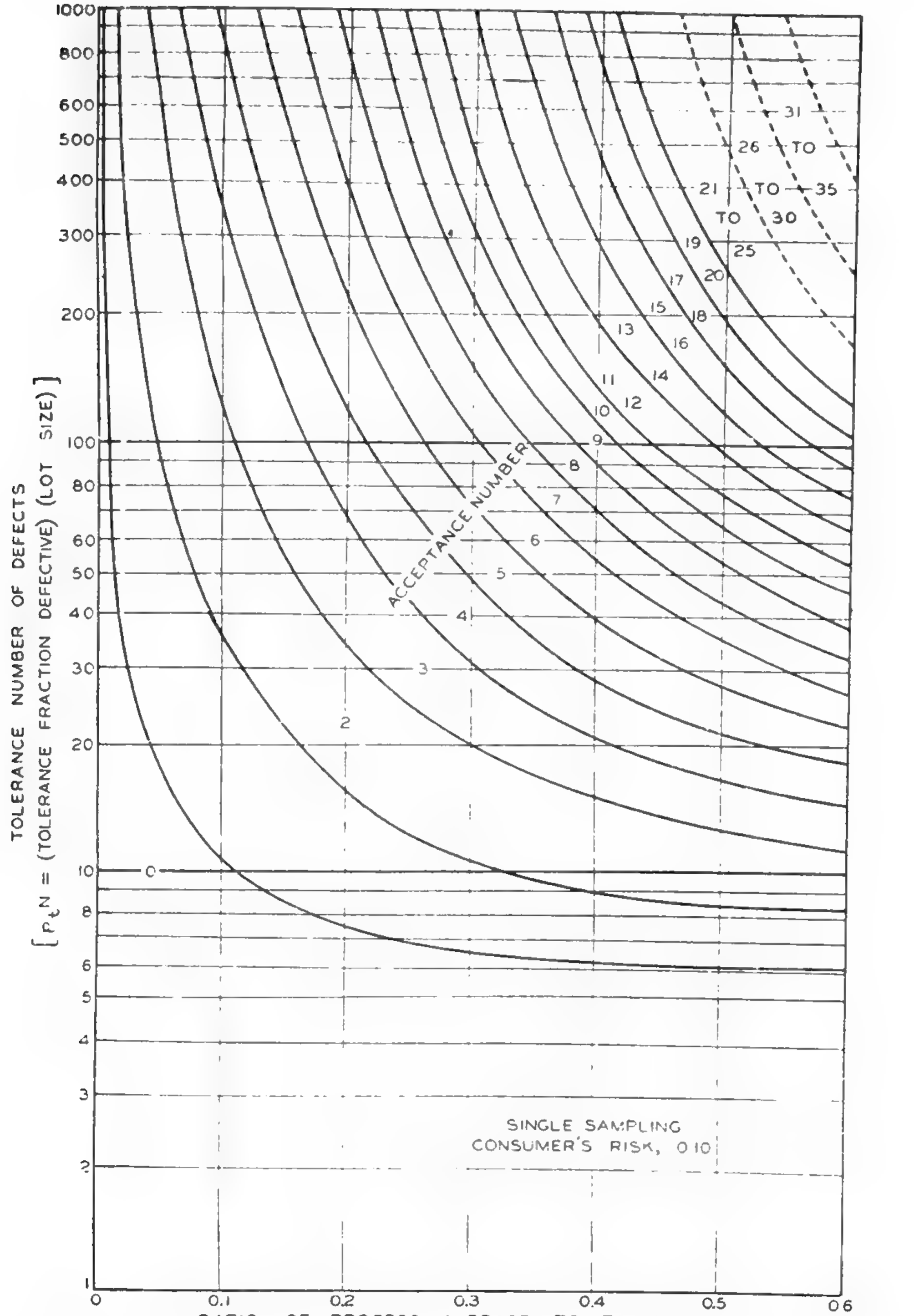


Fig. 7.—Chart for Finding Acceptance Number

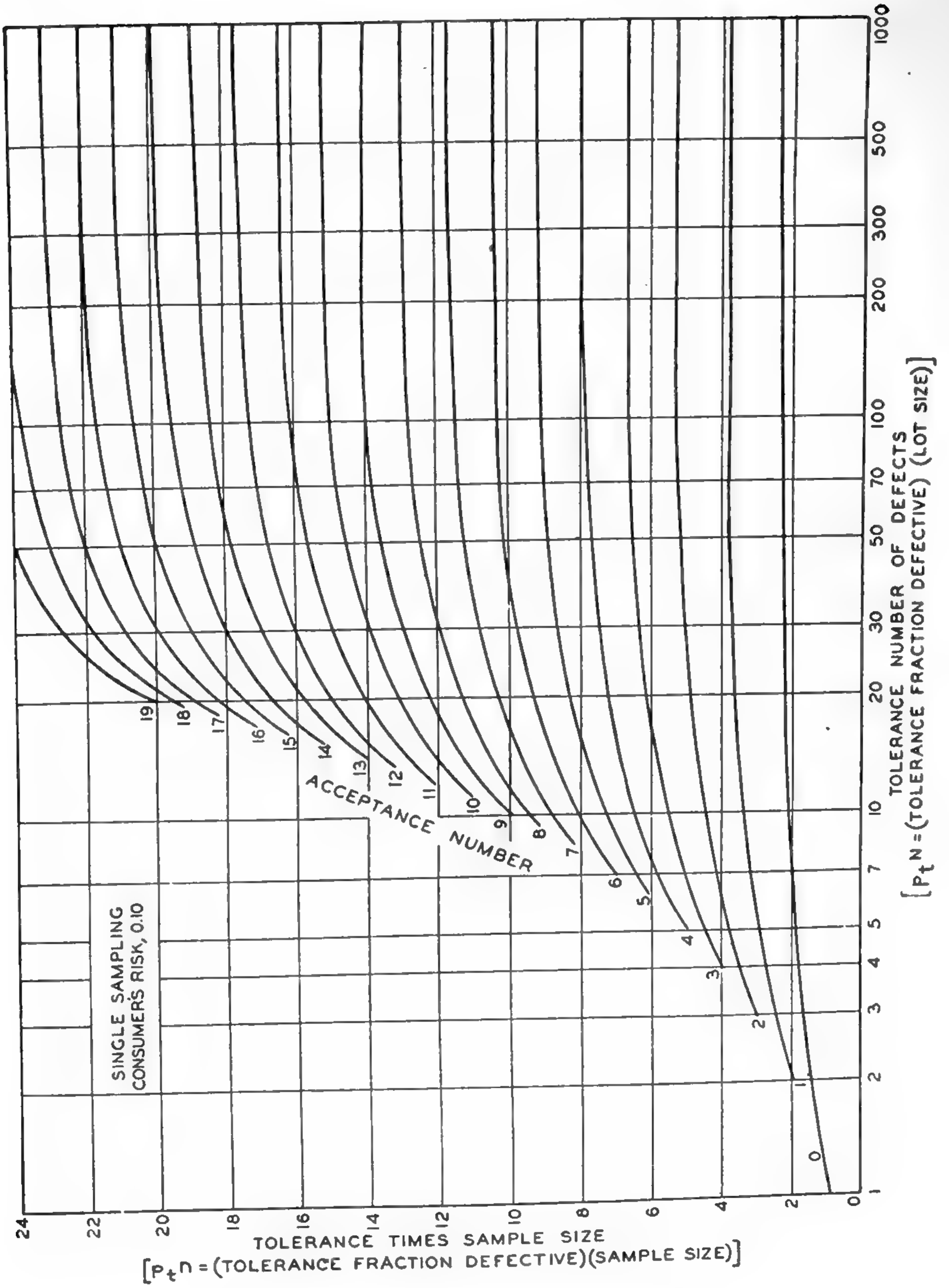


Fig. 8.—Curves for Finding Size of Sample

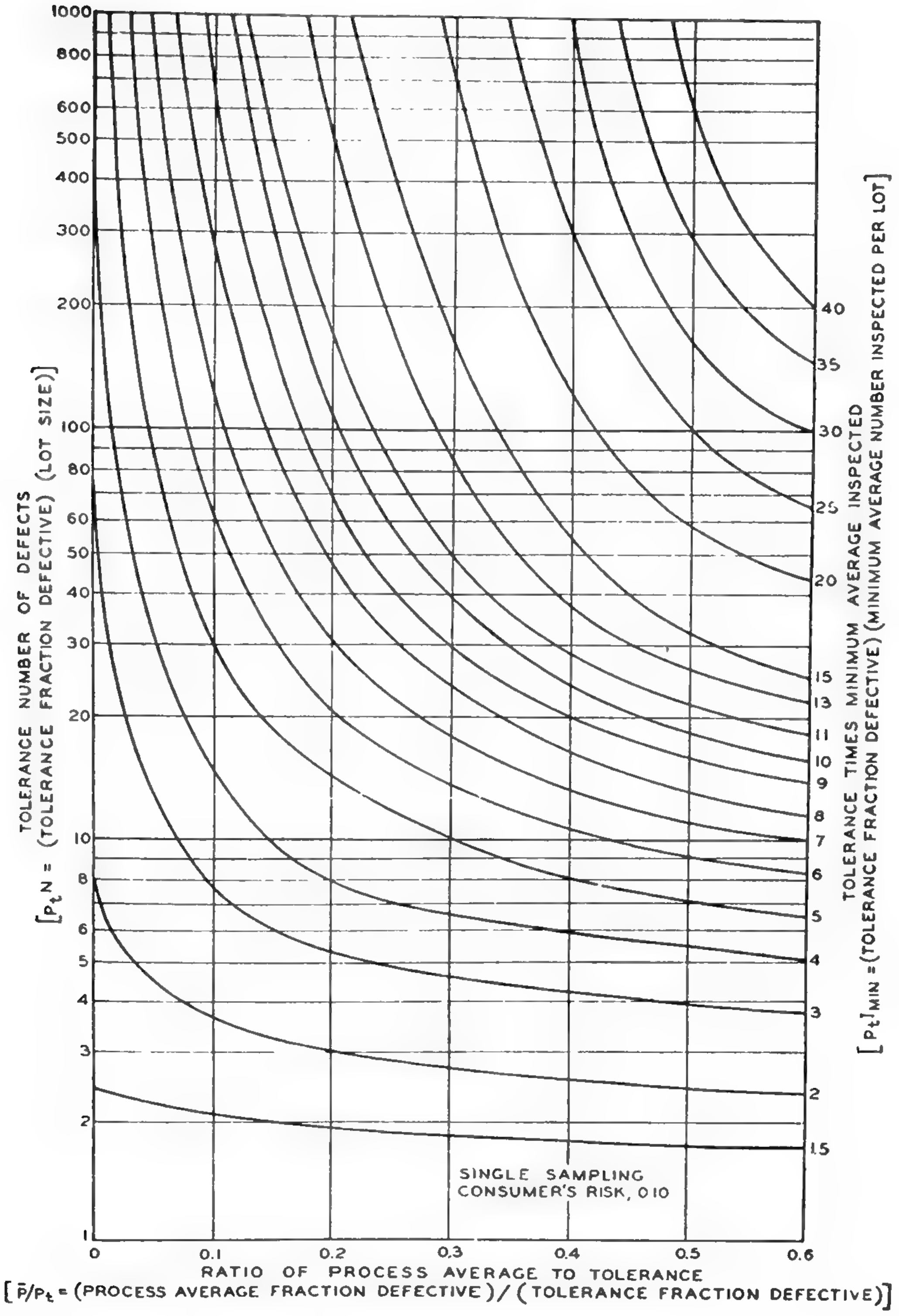


Fig. 9.—Curves for Finding the Minimum Amount of Inspection per Lot

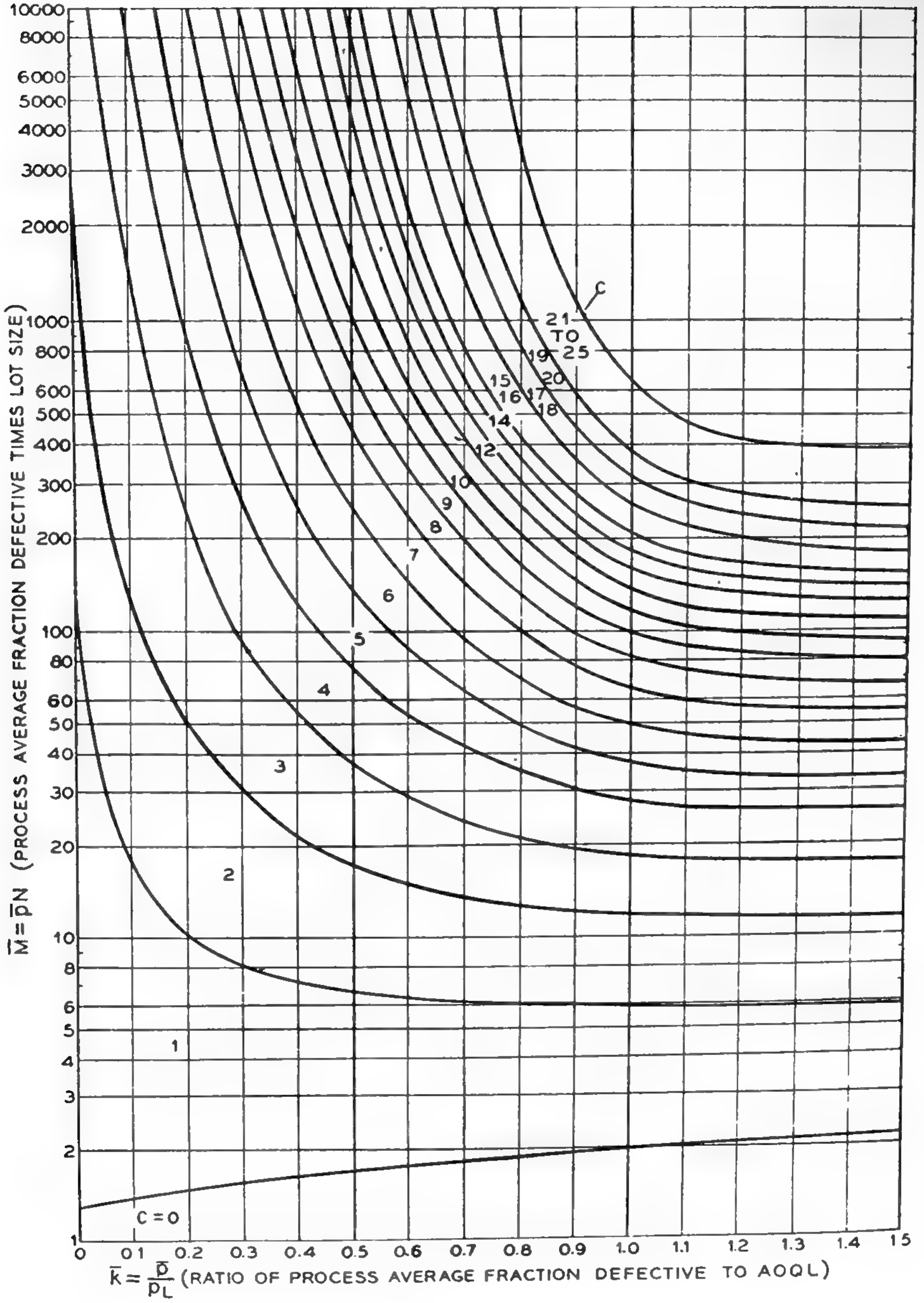


Fig. 10.—Chart for Determining Allowable Defect Number—AOQL Protection

Acceptance number $c = 9$
$p_t n = 14$
Sample size, $n = 14/p_t = 14/0.05$
$n = 280$

Referring to Fig. 9
$\bar{p}/p_t = 0.3$
$p_t N = 250$
$p_t I$ min. $= 17$
Min. Av. Inspected, I (min.) $=$ $17/0.05 = 340$

SOLUTION:

1. Sampling plan: $n = 280$, $c = 9$.
2. Average amount of inspection per lot $= 340$.

If the requirements of the problem are based on *AOQL* instead of Lot Tolerance Fraction Defective, use Fig. 10 to find the acceptance number c. With c, P_L and N given and y from Table 3 solve for n in the following equation:

$$n = \frac{yN}{P_L N + y} \tag{25}$$

Table 3—Solution of y, in Determining AOQL Sample Size

c	y	c	y	c	y
0	0.3679	9	5.836	18	12.38
1	0.8408	10	6.635	19	13.14
2	1.372	11	7.234	20	13.88
3	1.946	12	7.948	21	14.66
4	2.544	13	8.677	22	15.42
5	3.172	14	9.404	23	16.18
6	3.810	15	10.12	24	16.97
7	4.465	16	10.87	25	17.73
8	5.150	17	11.63	26	18.54
				27	19.30

Double Sampling Plan.—The double sampling plan is similar in principle to the single sampling plan with the exception that when a sample fails, another sample is drawn and both samples considered. The second sample is drawn only if the number of defects in the first sample exceeds a limiting value c_1 but is less than c_2. The lot is given a second chance. In addition to the psychological satisfaction of being doubly sure before rejecting a lot, the inspection efficiency is increased, especially for large lots with a low process average. Charts and tables for the solution of the double sampling plan similar to the above illustration for the single sampling plan are available.

Destructive Sampling Plans.—The Dodge-Romig plan assumes non-destructive inspection of at least the effective portion of the sample, since lots whose samples are unacceptable must be detailed 100%. When the test is destructive the lot must be either accepted or rejected completely on the basis of the sample result. While the net cost of sampling may become high, the sampling plans are usually somewhat simpler to construct than the Dodge-Romig plan. There are numerous references to such plans in the literature, some of which are given in the bibliography at the end of this chapter. These methods are equally applicable to the destructive testing of welded parts such as bend or break tests which may be part of the inspection plan.

Sequential Analysis

In the solution of any of the classical sampling procedures an *a priori* estimate must be made of the parent lot quality (standard deviation) before it is possible to determine the necessary sample size. This is an obvious disadvantage since the accuracy of the sample size determination depends on the accuracy of the quality estimate. Obviously, if the lot quality were accurately known in advance, there would be no need for sampling. If for production reasons or other scheduling requirements, it is necessary to select a single predetermined size of sample, the classical sampling methods with this attendant disadvantage must be used. On the other hand, if the sample size need not be predetermined, it is possible to use a method of multiple sampling with which no prior estimate of the lot quality is necessary. This method is called *Sequential Analysis* and is the outgrowth of double and multiple sampling plans. The number of observations is not determined in advance but depends on the results of the observations which have already been made. The big advantage gained by this method of sampling is the fact that a saving of about 50% in the number of observations over the most efficient test procedure based on a fixed sample size will often result.

The sequential analysis method is essentially a *test of hypothesis*. For example, hypotheses could be set up as follows: (*a*) a lot of material is below specification quality, (*b*) there is an improvement in weld ductility for electrode *A* vs. electrode *B*, (*c*) variation in aluminum spot weld shear strength as a result of surface oxide remover *X* exceeds a minimum value, etc. After each observation is made, the operator must

make one of the following decisions: (1) accept the hypothesis, (2) reject the hypothesis, (3) continue by taking an additional unit for inspection. The number of observations required depends on the quality of the product, the results of inspection, and the probability of making errors of type 1 and type 2 (the probability of rejecting the hypothesis when the hypothesis is true and the probability of accepting the hypothesis though the hypothesis is false).

A sequential analysis problem can be solved either by tabular or graphical means. The solution of a typical problem is shown in graphical form in Fig. 11.

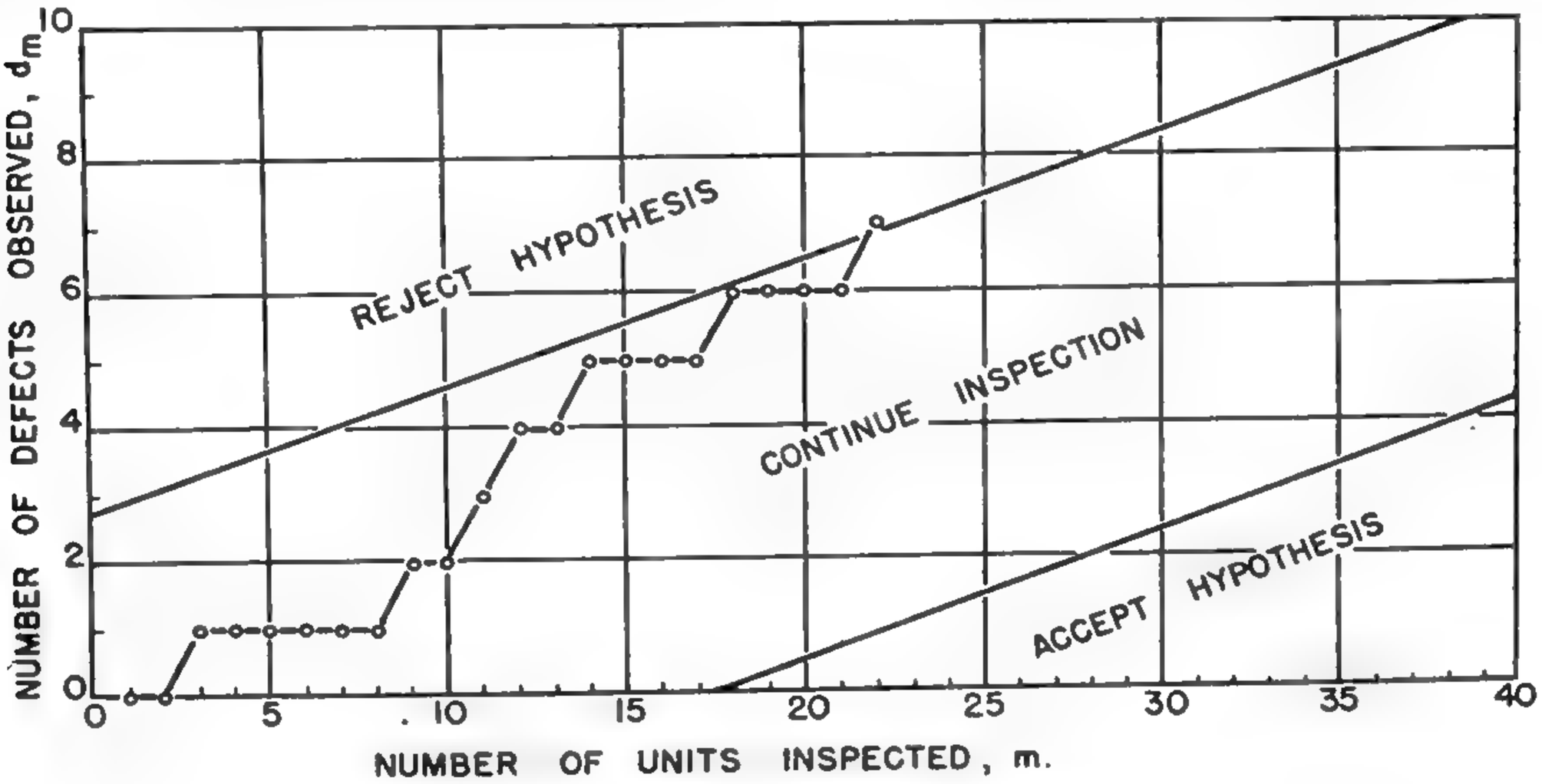


Fig. 11.—Graphical Solution for Sequential Analysis Test

The mechanics of the solution involve determining the equations for the two parallel lines representing the operational limits of inspection (or the acceptance and rejection numbers for the tabular solution).*

Quality Control Methods

Control Chart.—No amount of inspection can improve the quality of a product and the simple act of separating the good from the bad without inquiring into the cause of defective parts does not constitute quality control. On the other hand, to look for trouble whenever the quality characteristic varies is both unwise and uneconomical. It was previously shown that there is inherent variation in any product. Random variations which are due to pure chance are inherent in any process and cannot be eliminated. Variations which are due to *assignable causes*** indicate lack of statistical control. Assignable causes of variation can and in most cases should be identified and removed.

The Control Chart is a useful and effective technique developed by W. Shewhart for determining lack of statistical control by detecting variations in quality which are greater than can be attributed to chance alone. Determining the cause of variation and its removal is an engineering problem.

The control chart technique emphasizes the chronological order in which the samples are made. No change is initially made in the method of inspection, but merely in the method of treating and recording the data. Instead of simply tabulating the data, they are immediately plotted on a chart in horizontal sequence. The chart has a central line and an upper and lower control limit (Fig. 12). So long as the data are randomly dispersed about the central line and remain between the control limits, the most positive kind of assurance is had that the process is in statistical control. With control, predictions based on the percent of product which lies between limits can be made with a high degree of accuracy since most industrial processes can be closely approximated by the normal distribution

* See references 20 and 25 in the bibliography.

** W. Shewhart defines an assignable cause of variation as "...one that can be found by experiment without costing more than it is worth to find it."

after a state of statistical control has been attained.

Establishment of Control Limits.—The choice of control or action limits is essentially an attempt toward an economic balance between the two possible types of error.

1. Looking for trouble that does not exist.
2. Not looking for trouble that does exist.

The limits are determined by the fact that it is unlikely that a mean of a sample size n will deviate from the mean of the lot by more than 3 standard errors ($3\sigma/\sqrt{n}$) more than 3 times in 1000.

four pieces in a box). A sample consists of a subgroup, the size of which should receive careful consideration. When the quality characteristic is measured by the method of variables large subgroups are undesirable because important causes of variation may easily be masked. Assignable causes are usually periodic and of short duration and would, therefore, have little effect on a large sample. It is always desirable to have the subgroups small enough so that one can assume that each subgroup was made under essentially the same conditions. On the other han ,

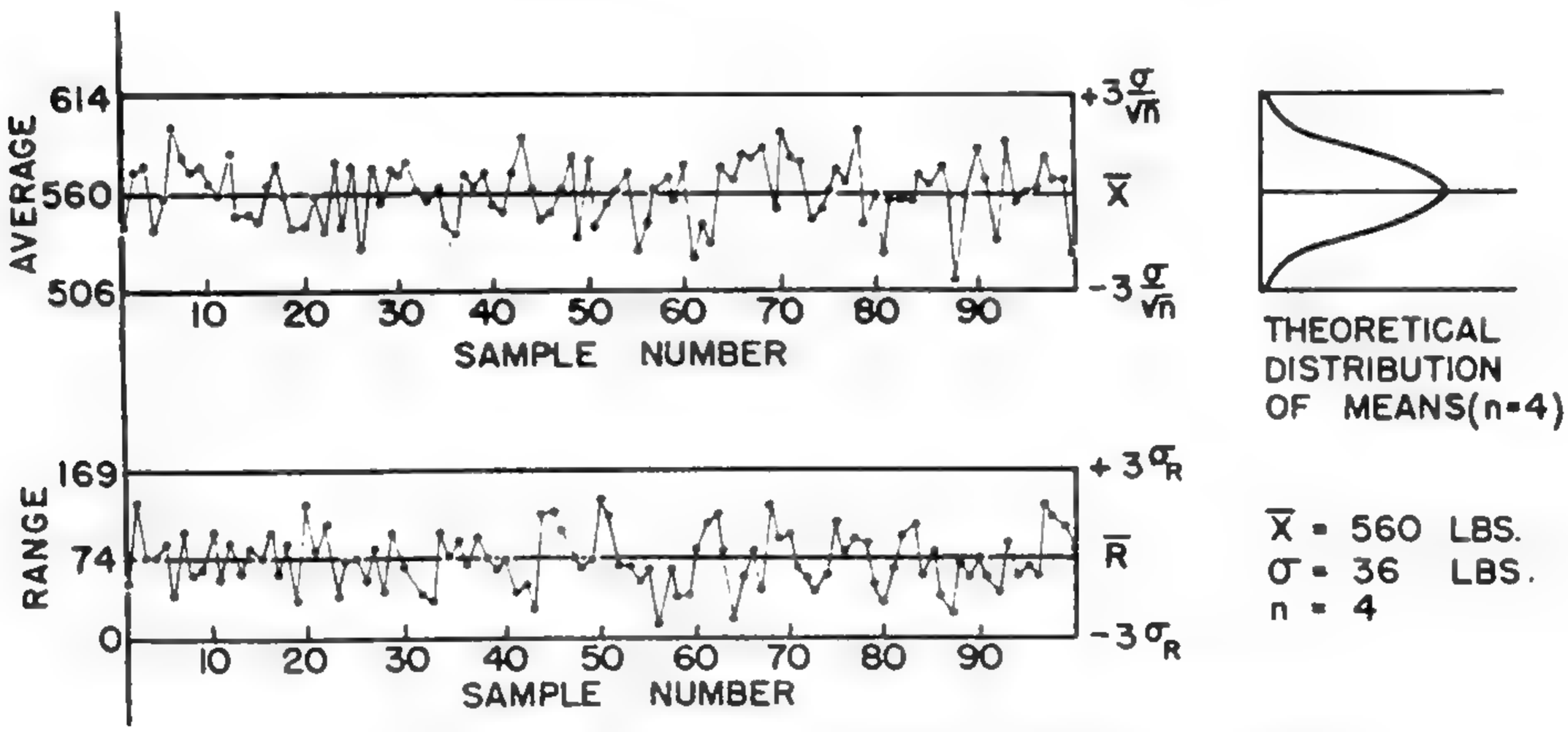


Fig. 12.—Control Chart for Average and Range, Shear Strength of Spot Welds, 24S-T Alclad Aluminum Alloy, 0.040 to 0.040 Sheet

Procedure for Setting Up Control Limits.

A. Quality Characteristic: The particular quality characteristics for which the part is inspected depend, of course, on the functional requirements of the part, i.e., shear strength, breakdown voltage, hardness, dimensions, etc. However, it is often advisable to set up control charts during intermediate steps in the process for the analysis of characteristics which may only indirectly affect the ultimate requirement. Such a procedure requires a careful analysis of the production process and a flow sheet for the strategic location of control charts.

B. Sampling: Samples should be taken at frequent time intervals and recorded on the control chart in their sequence of manufacture in so far as possible. Bias can often be reduced by the simple safeguard of avoiding rigid time or location sampling (every hour on the hour, first

subgroups of $n \leqq 3$ should not be used unless absolutely necessary and some knowledge of the general distribution is known (seldom the case during initial stages of inspection). Rational subgroups of $n = 4$ are ideal for the following reasons:

1. Distribution of means for $n \geqq 4$ is approximately normal.
2. Subgroups of 4 are sensitive to variations due to assignable causes.
3. Each subgroup is probably made under essentially the same conditions.

It is always better to take frequent small samples than infrequent large samples.

When the quality characteristic is measured by the method of attributes (go no-go), the control chart is more efficient when the sample is comparatively large. For practical purposes, the sample should be large enough so that the expected number of defects per sample is at least 4 ($pn = 4$, where p is the expected

fraction defective and n is the sample size).

C. Choice of Statistic: Control Charts can be made for any statistical quantity which may be indicated by the requirements of the process. Ordinarily, the statistics for average $\bar{X}$, standard deviation σ, range R and fraction defective p will cover most industrial cases. When the quality characteristic is inspected by the method of variables, a control chart for the average $\bar{X}$, and standard deviation σ, will give all the information required. Since data are often taken and computed on the shop floor, it is an advantage to substitute the range of each sample for the standard deviation. The loss of mathematical efficiency where the sample size is less than 8 is insignificant and more than compensated by the resulting saving in time and reduced chance of computation error.

When the quality characteristic is inspected by the method of attributes, the standard deviation is a function of the fraction defective and sample size. All the required information will, therefore, be in a single control chart for fraction defective p.

Nomenclature Used in Control Chart

X = a single measured value (shear strength, hardness, carbon content, etc.).

$\bar{X}$ = the arithmetic mean or average of a series of measured values from a sample of n pieces.

$\bar{\bar{X}}$ = the average of a set of $\bar{X}$ values from a series of samples.

$\bar{X}'$ = the true or estimated average of the grand lot or process.

σ = the standard deviation, the root-mean-square deviation about the average $\bar{X}$, for a sample of n pieces.

$\bar{\sigma}$ = the average standard deviation of a set of σ values from a series of samples.

σ' = the true or estimated standard deviation of single observations of the grand lot or process.

R = the range, the difference between the largest and smallest observed value from a sample of n pieces.

$\bar{R}$ = the average value of a set of R values from a series of samples.

p = the fraction defective of a sample of n pieces.

$\bar{p}$ = fraction defective in a complete set of records or average of a set of p values from a series of samples.

p' = the true or estimated fraction defective of the grand lot or process.

c_2 = a constant, which varies with n that relates σ' to the $\bar{\sigma}$ of the distribution for σ for samples of n pieces ($\bar{\sigma} = c_2\sigma'$).

d_2 = a constant, which varies with n, that relates σ' to the $\bar{R}$ of the distribution of R for samples of n pieces ($R = d_2\sigma'$).

n = sample size.

*Construction of Control Chart Limits**

A. Method of Variables

I. When records are available, determine grand average $\bar{\bar{X}}'$ and standard deviation σ' from not less than 200 observations. Control Chart Limits are computed as follows:

a. Control Chart for Sample Average $\bar{X}$

Central Line = $\bar{\bar{X}}'$

Control Limits = $\bar{\bar{X}}' \pm 3\sigma'/\sqrt{n}$

or $\bar{\bar{X}}' \pm A\sigma$ (26)

b. Control Chart for Standard Deviation σ

Central Line = $c_2\sigma'$

Control Limits = $c_2\sigma' \pm 3\sigma'/\sqrt{2n}$

or $B_1\sigma'$ and $B_2\sigma'$ (27)

c. Control Chart for Range R

Central Line = $d_2\sigma'$

Control Limits = $D_1\sigma'$ and $D_2\sigma_1$ (28)

II. When past records are unavailable and $\bar{\bar{X}}'$ and σ' are unknown, determine $\bar{\bar{X}}$ and $\bar{\sigma}$ or $\bar{R}$ from a series of not less than 50 samples. Control Chart Limits are computed as follows:

a. Control Chart for Sample Average $\bar{X}$

Central Line = $\bar{\bar{X}}$

Control Limits = $\bar{\bar{X}} \pm 3\bar{\sigma}/c_2\sqrt{n}$

or $\bar{\bar{X}} \pm A_1\bar{\sigma}$

or $\bar{\bar{X}} \pm A_2\bar{R}$ (29)

b. Control Chart for Standard Deviation σ

Central Line = $\bar{\sigma}$

Control Limits = $\bar{\sigma} \pm 3\bar{\sigma}/c_2\sqrt{2n}$

or $B_3\bar{\sigma}$ and $B_4\bar{\sigma}$ (30)

c. Control Chart for Range R

Central Line = $\bar{R}$

Control Limits = $D_3\bar{R}$ and $D_4\bar{R}$ (31)

B. Method of Attributes, Fraction Defective

I. When past records are available, determine p'. Control Chart

* See Table 4 for constants.

Limits are computed as follows:

Central Line $= p'$

$$\text{Control Limits} = p' \pm 3\sqrt{\frac{p'(1-p')}{n}} \quad (32)$$

II. When past records are unavailable, determine $\bar{p}$ from a series of sample ($pn \geqq 4$) or a sufficiently large sample.

Central Line $= \bar{p}$

$$\text{Control Limits} = \bar{p} \pm 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}} \quad (33)$$

Indications of Lack of Control

The control chart is a particularly useful tool because it graphically presents a complete running picture of the process, past and present, and very often an indication of what may happen in the future before the damage has been done and while there is still time to prevent it. Because the principal function of the control chart is to indicate the presence of random variations from a single, causal system as evidence of the existence of statistical control, it is important to be able to recognize the order of plotted points as being random or non-random. Since there are no mathematical expressions which verify purely random variations as such, the experience of the operator becomes the judge as to whether the variations of the process correspond to the type of variations which he would expect if chips were randomly selected from a bowl. The following criteria are suggested as indicating lack of statistical control. It is only with the control chart that these criteria become an operational basis for deciding when to look for trouble.

1. Points falling outside of control limits.
2. Runs in an upward or downward direction.
3. Runs of six or more samples above or below the central line.

None of the above criteria is conclusive evidence of lack of control since there are innumerable ways in which a series of numbers may be selected in a purely random manner. However, the appearance of any of the above criteria resulting from random selection is highly improbable and investigation is economically justifiable.

Invariably, the introduction of the control chart to an inspection system will reveal evidence of lack of statistical control. As the assignable causes are investigated and removed, the parameters, average and standard deviation, will change and necessitate recalculation of control limits. When statistical control has been attained, reduction in the frequency of sampling will be possible without sacrifice in quality protection. When all assignable causes are removed, and the process is in control, nothing further can be done to reduce the variability of the product without changing the process.

Summary Procedure for Quality Control

1. Design random sampling procedure and obtain representative data from each producing unit.
2. Plot results of samples immediately on control chart.
3. Determine whether process is in statistical control.
4. Remove assignable causes of variation when found.
5. Recompute control chart limits.
6. Apply control chart data to acceptance sampling plan and specifications.

Process Minimums

Sampling inspection and the control chart plans are the most widespread applications of industrial statistical techniques. Familiarity with the fundamentals of statistical analysis and a little ingenuity will often suggest new applications of accepted techniques for certain specialized problems.

One such problem arises in the production of spot welds which are subject to minimum shear strength specifications, though the method can be applied to other cases of inspection by variables where minimum values are of interest. In order to insure that some large percentage of the process falls above the *Specification Minimum*, the process average must be considerably above specification minimum. The position of the process average is determined by the allowable fraction below the specification minimum (fraction defective), and the inherent spread or variation (σ) of the process. The quality of the process is customarily determined by taking random samples from each machine during production runs. The results of these random-check data should

be plotted on a control chart. A problem presents itself in setting up a machine for spot welding since the operator attempts to predict from his set-up sample whether the results of that particular machine setting (as will be shown by the random-check data) will meet the specification requirements. It is the usual procedure for the operator to set the machine variables according to some predetermined schedule which should produce satisfactory welds for a given combination of thicknesses. He welds a sample of two or more specimens and tests them to destruction on a tensile machine. If the average shear strength of the sample is above a certain value which will be called the *process minimum*, the operator will proceed to weld the parts for which the machine was set up. If the average does not meet the process minimum value he will make some small adjustment in the settings and make a satisfactory sample or report to his supervisor that the machine requires mechanical attention. If the process minimum is placed excessively high in order to insure a large percent being above specification minimum, the operator may experience difficulty in meeting this value; if the process minimum is too low, an excessive fraction of the production may be below the specification minimum.

A study of Fig. 13 shows what happens when a machine is adjusted to a weld quality $\bar{X}_p$, the lot tolerance average, with a corresponding fraction defective p_t and standard deviation σ. The process minimum is located with reference to the distribution of means so that the area to the right of the process minimum is 10%.* If the set-up sample average is less than the process minimum the sample will be rejected, and conversely, if the set-up sample is greater than the process minimum, the sample will be accepted. Therefore, if $\bar{X}_p$ represents the quality of the grand lot, samples from this lot will be accepted only 10% of the time, even though $\bar{X}_p$ represents a lot of just lot tolerance quality. This area, Consumer's Risk, is the probability of accepting a sample of lot tolerance quality. If the grand lot becomes worse than $\bar{X}_p$ for a fixed process minimum (the distribution shifts to the left), the consumer's risk area, or probability of accepting becomes much smaller than 10% while if the quality improves (the distribution shifts to the right) the probability of accepting increases. The consumer's risk is 10% only when the process is of exactly lot tolerance quality. Since the distribution of means is normal even though the original distribution may not be, the normal integral

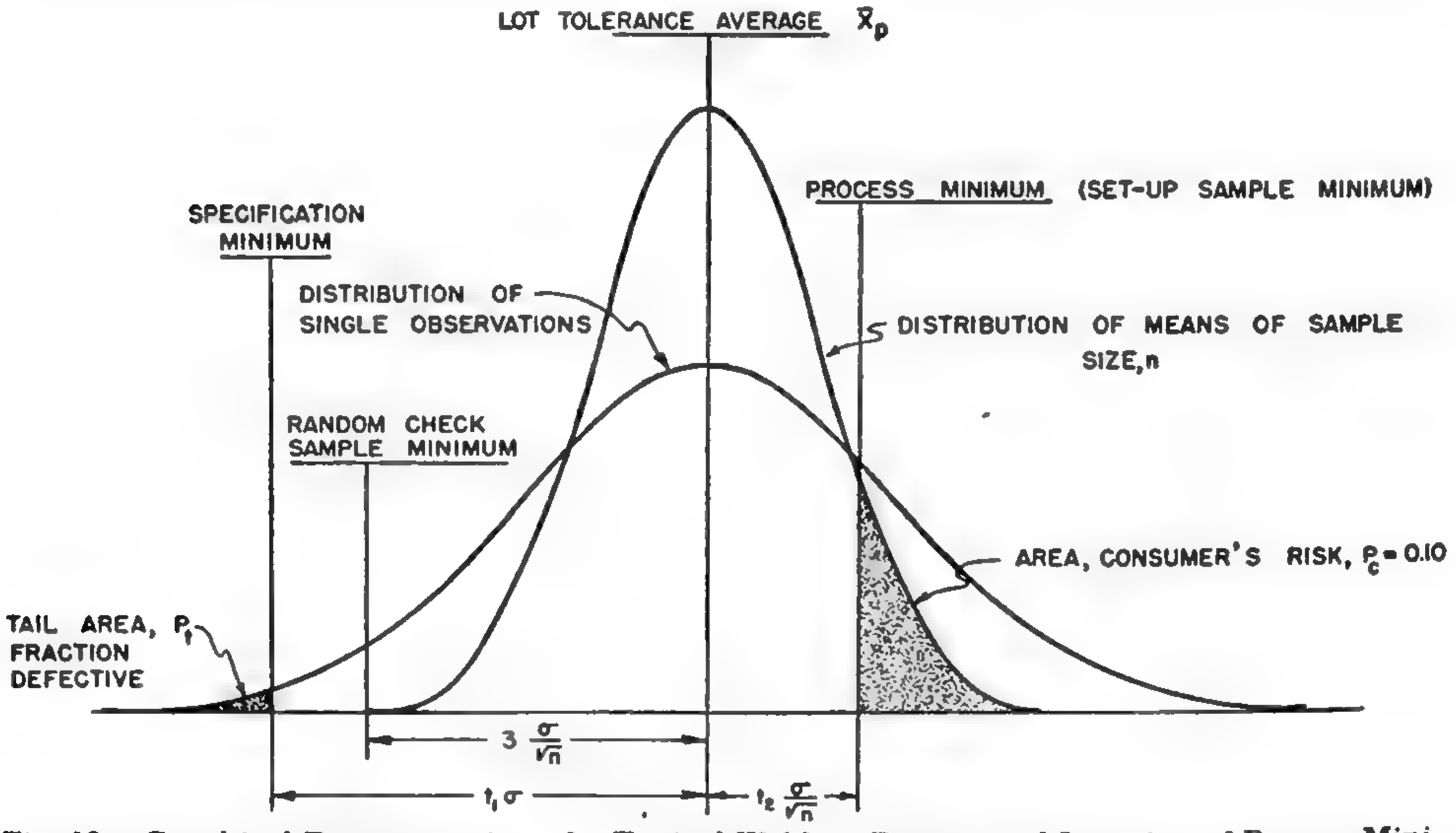


Fig. 13.—Graphical Representation of a Typical Welding Process and Location of Process Minimum

* Ten percent of the total area under the distribution of means.

tables may properly be applied to locate the position of the process minimum. The location of the process minimum can be expressed in terms of the specification minimum, the standard deviation σ, and the sample size by the following relationship:

$$\begin{aligned}\text{Process minimum} &= \\ &\text{Spec. Min.} + (t_1\sigma' + t_2\sigma'/\sqrt{n}) \\ &\text{Spec. Min.} + \sigma'(t_1 + t_2/\sqrt{n}) \\ &\text{Spec. Min.} + Q\sigma' \qquad (34)\end{aligned}$$

where

σ' = Standard deviation of single observations for the process (determined from past random-check data or control chart).

n = sample size.

t = the ordinates of the distribution in units of σ which include the area concerned (see Table of Normal Integral).

Q = constant, which varies with n and the fraction defective. See Table 5 $[Q = (t_1 + t_2/\sqrt{n})]$.

Examination of the formula for the process minimum shows that when the value of the process minimum becomes excessive, it can be reduced by (*a*) reducing the variability, σ', of the process, (*b*) increasing the sample size. If neither of these alternatives is possible or desirable, either the specification minimum must be reduced or the allowable fraction defective increased.

Referring again to Fig. 13, it will be noted that the process minimum is considerably higher than the acceptable minimum value of the random-check sample. The minimum value of the random-check sample is the same as the lower *Control Chart Limit* for sample averages. The control chart limits are computed as shown on page 1033 but the minimum value that the lower control limit can become is determined by the following relationships:

$$\begin{aligned}\text{Minimum lower control chart limit} &= \\ &\text{Spec. Min.} + (t_1\sigma' - A\sigma') \\ &\text{Spec. Min.} = \sigma'(t_1 - A) \\ &\text{Spec. Min.} = L\sigma' \qquad (35)\end{aligned}$$

where:

A = a constant, see Table 4 $(A = 3/\sqrt{n})$

L = a constant, see Table 6 $[L = (t_1 - A)]$

t_1 = function of allowable fraction defective (from Table of Normal Integral).

Table 4—Factors for Computing Control Chart Lines—Small Samples

Number of Observations in Sample, n	Chart for Averages: Factors for Control Limits A	Chart for Averages: Factor for Central Line A_1	Chart for Standard Deviations: Factors for Control Limits B_1	Chart for Standard Deviations: Factors for Control Limits B_2	Chart for Standard Deviations: Factor for Central Line B_3	Chart for Standard Deviations: Factor for Central Line B_4	Chart for Ranges: Factors for Control Limits D_1	Chart for Ranges: Factors for Control Limits D_2	Chart for Ranges: Factors for Control Limits D_3	Chart for Ranges: Factors for Control Limits D_4	Chart for Ranges: Factor for Central Line d_2
2	2.121	3.759	0	1.410	0	3.658	0	3.686	0	3.268	1.128
3	1.732	2.394	0	1.277	0	2.692	0	4.358	0	2.574	1.693
4	1.500	1.880	0	1.175	0	2.330	0	4.698	0	2.282	2.059
5	1.342	1.596	0	1.094	0	2.128	0	4.918	0	2.114	2.326
6	1.225	1.410	0.003	1.028	0.003	1.997	0	5.078	0	2.004	2.534
7	1.134	1.277	0.086	0.973	0.097	1.903	0.205	5.203	0.076	1.924	2.704
8	1.061	1.175	0.153	0.925	0.169	1.831	0.387	5.307	0.136	1.864	2.847
9	1.000	1.094	0.207	0.884	0.227	1.774	0.546	5.394	0.184	1.816	2.970
10	0.949	1.028	0.252	0.848	0.273	1.727	0.687	5.469	0.223	1.777	3.078

There are two minimum values which guarantee the requirements of the specification: the process minimum for set-up samples and the minimum lower control chart limit for the random-check samples. It will be noted that the numerical value of the average shear strength does not have to be determined. The following example will illustrate the calculations for these values:

Given:

Maximum percent defective..	0.5%
Consumer's Risk (max. probability of accepting lots 0.5% defective or worse).....	10%
Set-up sample size.....	4
Random-check sample size...	4
Specification Minimum (0.040 gage 24S-T Alclad).....	345 lb.
Standard Deviation, σ' (from past random-check data)...	36 lb.

Find:

1. Process minimum.
2. Minimum value of lower control chart limit.

Calculations:

1. Process minimum = Spec. Min. + $Q\sigma'$(Q from Table 5) = 345 + 3.216×36 = 461 lb.
2. Minimum value for lower control chart limit = Spec. Min. + $L\sigma'$(L from Table 6) = 345 + (1.076×36) = 384 lb.

Table 5—Values of Q, Solving for Process Minimum

n	$p_t \rightarrow$	Allowable Percent Defective								
		0.001	0.005	0.010	0.100	0.500	1.000	2.500	5.000	10.000
2		5.2	4.8	4.605	3.995	3.481	3.231	2.865	2.550	2.186
3		5.0	4.6	4.440	3.830	3.316	3.066	2.700	2.385	2.021
4		4.9	4.5	4.340	3.730	3.216	2.966	2.600	2.285	1.921
5		4.9	4.5	4.273	3.663	3.149	2.899	2.533	2.218	1.854
6		4.8	4.4	4.223	3.613	3.099	2.849	2.483	2.168	1.804
7		4.8	4.4	4.183	3.573	3.059	2.809	2.443	2.128	1.764
8		4.8	4.4	4.153	3.543	3.029	2.779	2.413	2.098	1.734
9		4.7	4.3	4.127	3.517	3.003	2.753	2.387	2.072	1.708
10		4.7	4.3	4.105	3.495	2.981	2.731	2.365	1.050	1.686

APPLICATION OF STATISTICAL CONCEPTS IN CONNECTION WITH DRASTIC TESTING

Drastic Tests and the Reasons for Their Use

There are many cases where a finite chance of failure cannot be tolerated, and with these, cases of the development of new products and methods to meet more demanding requirements than are currently being satisfied. Such problems introduce the use of tests made under conditions more severe than are usually encountered in service. These tests are frequently called *drastic tests*, or in cases where failure develops slowly in service, *accelerated tests*.

The use of drastic tests is primarily a laboratory method, as distinguished from straight plant inspection, and in processes such as welding, where exact repetition of method and exact physical measurements are difficult or impossible, statistical analysis of such tests is often the best available tool for research. In addition to their value as disaster insurance, these tests are frequently valuable in reducing the labor of a laboratory investigation. Thus, for examples previously shown for the establishment of sample size by the Binomial or Poisson distributions, the required number of samples or of failures may be obtained with far less material if the test is conducted at an elevated level bearing some known relationship to the service condition. In other cases, the service failures may occur only after prolonged use, and the drastic tests may be required to obtain laboratory failures within a time such that the results of the test may be currently useful.

It must be emphasized that it is always necessary to exercise good judgment to insure that the mechanism of failure under the drastic test is the same as the mechanism which operates less frequently in the field. Careful mathematical treatment of the test results is necessary to relate them properly to service conditions, and good statistical control is required to determine their significance. The theory and practice of such interpretation is admittedly in an early stage of development and worthy of further study.

Certain jobs like the production of welded pressure vessels or boilers lend themselves naturally to a proof test of the finished product, wherein all parts

are exposed to a stress somewhat larger than is expected in practice. This guards against the presence of serious defects, but as the proof load is limited by the necessity of avoiding permanent deformation, and as some failures may develop slowly, as by corrosion or metallographic changes, the test cannot give complete assurance of safety. Tests of special coupons to destruction will give a better idea of the true strength of the product, but naturally will leave some doubt as to the accuracy with which the coupons duplicate the structure or state of stress of the production unit.

which is to be sustained in service, to establish an inspection test level. The level thus established is not one that all specimens ought to exceed, but one that exactly half of the specimens may legitimately be *required* to exceed. With this type of specification, the claim that a low test is an accident is eliminated, since all such accidents are accounted for in the chance factors forming the lower half of the distribution. It should also be noticed that the sensitivity or discrimination of the test has been greatly increased (or the necessary sample size decreased) since any lowering of the quality of the

Table 6—Values of L, Solving for Minimum Value of Lower Control Limit

		Allowable Percent Defective								
n	$p_t \rightarrow$	0.001	0.005	0.010	0.100	0.500	1.000	2.500	5.000	10.000
2		2.2	1.8	1.58	0.969	0.455	0.205	−0.161	−0.476[a]	−0.840[a]
3		2.6	2.2	1.97	1.358	0.844	0.594	0.228	−0.087[a]	−0.451[a]
4		2.8	2.4	2.20	1.590	1.076	0.826	0.160	0.145	−0.219[a]
5		3.0	2.6	2.36	1.748	1.234	0.984	0.618	0.303	−0.061[a]
6		3.1	2.7	2.48	1.865	1.351	1.101	0.735	0.420	0.056
7		3.2	2.8	2.57	1.956	1.442	1.192	0.826	0.511	0.147
8		3.2	2.8	2.64	2.029	1.515	1.265	0.899	0.584	0.220
9		3.3	2.9	2.70	2.090	1.576	1.326	0.960	0.645	0.281
10		3.4	3.0	2.75	2.141	1.627	1.377	1.011	0.696	0.332

[a] Limits below the specification minimum

In the usual *proof, drastic* or *destructive test* as applied to inspection, a factor of safety is chosen arbitrarily and it is then required that *all* specimens tested show strength or a similar property exceeding a value set by this factor of safety. An examination of a normal distribution curve, such as one of those in Fig. 14 shows that it may be impossible to expect *all* specimens in a lot to be stronger than specified unless the average strength is much greater than the specification, hence the finding of an occasional specimen below specification does not necessarily indicate that the product has gone bad, but only that the accidents of choice have turned up one of the pieces in the tail of the distribution curve. As a prelude to a rational specification, therefore, let the results of all tests be collected for a period, and these results be plotted to show the characteristic distribution within the lot of the product. (It will usually be sufficient to assume normality and determine only the standard deviation.) According to the degree of safety required in the product, let 3, 4 or 5 times the experimentally determined value of the standard deviation be added to the strength value

product is immediately shown by a large increase in the proportion failing to attain the test level when this level is set at the center of the distribution. (It will be recognized that this procedure which results in establishing a *process average* for zero allowable fraction defective is similar in principle to the Process Minimum Test (page 1035) though somewhat simpler to set up.)

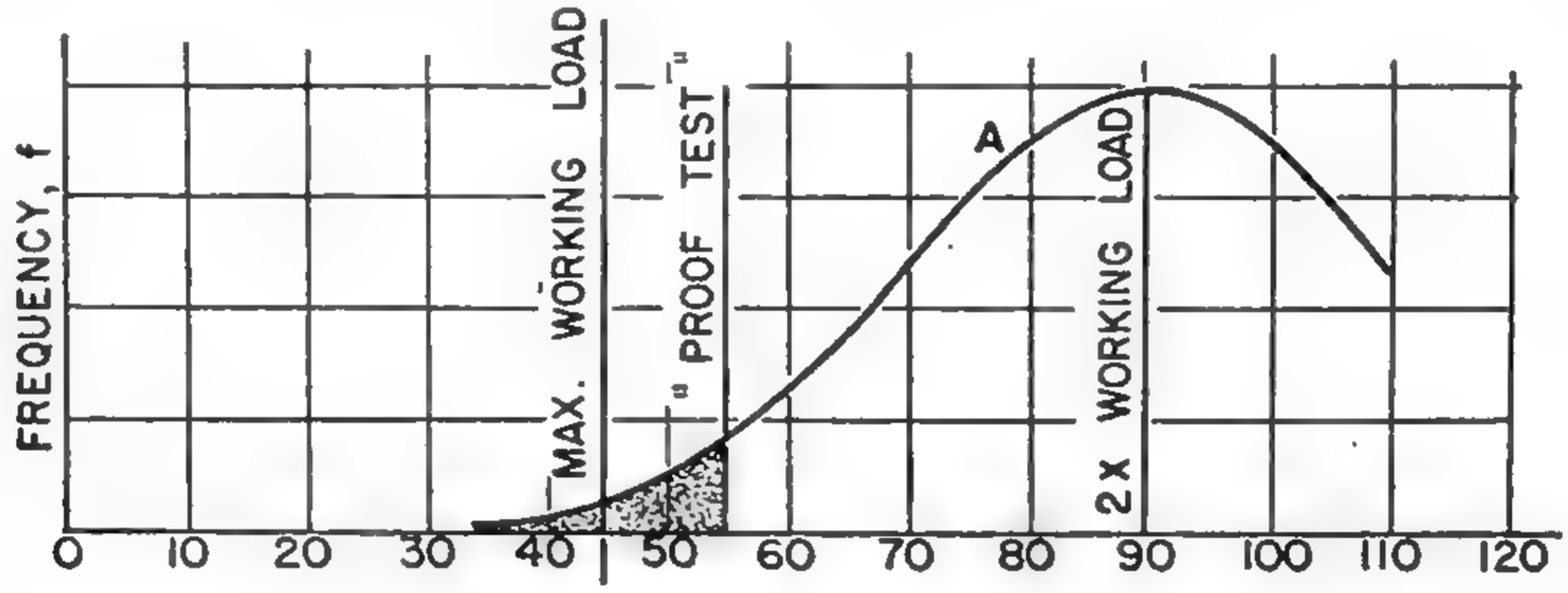
Quality Index for Evaluation of a Property in Terms of a Standard Material

In a research investigation of weld failures, such as, for example, hard zone cracking in manually arc-welded sections, it would be known that one heat of steel behaved well in practice, while another, perhaps of identical nominal composition but from a different source, frequently failed.* Obvious limitations on the control of the welding process prevent a study based on small changes of operating conditions, while ordinary physical tests become useless when it is shown that the stronger sections are more prone to cracking than the weaker, although not with any regular

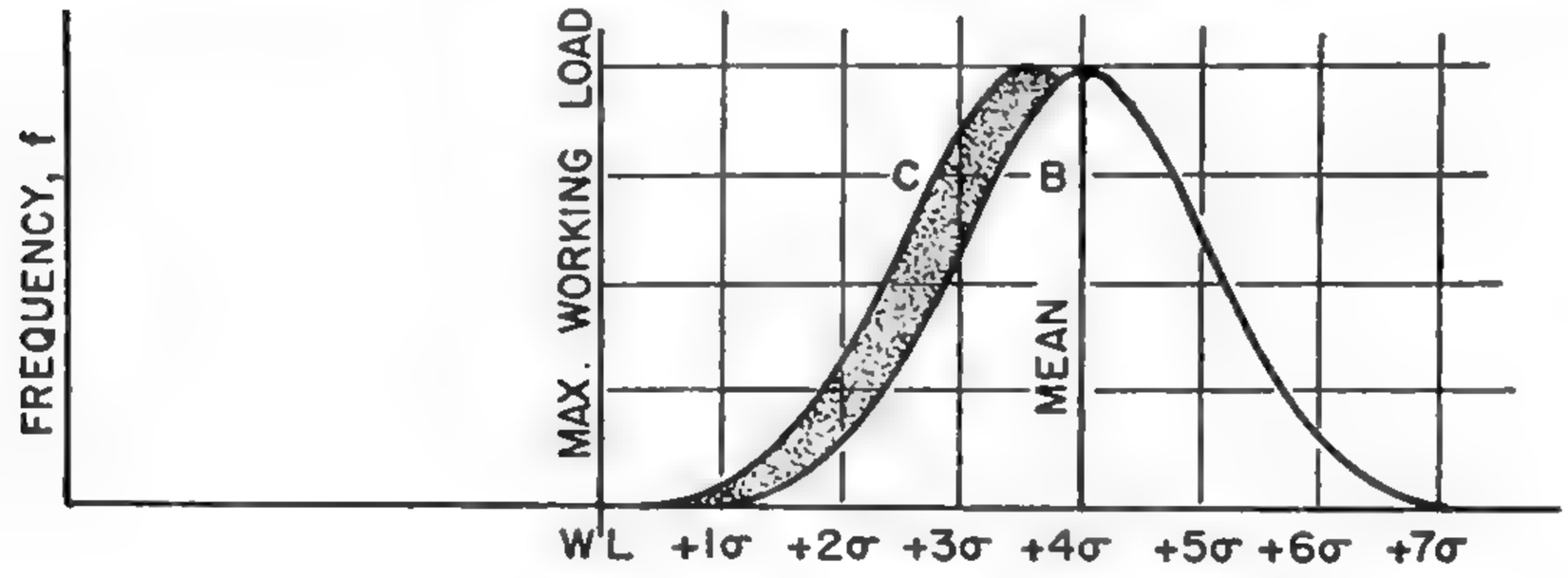
* See Reference 22 in the bibliography.

relationship. Under such conditions, an investigation toward a more reliable product must be based on an analysis of the prevalence of the cracks themselves, and therefore must be statistical in nature. Many other problems will of course be found similar in general nature.

as welds were made under field conditions, steel *S* often failed to crack at all, hence the superiority of the special heats was not apparent, and the inferiority of heat *T* appeared more or less important from time to time. A change to more severe welding conditions produced some cracks



A: "FACTOR OF SAFETY" MAY NOT ELIMINATE ALL FAILURES PROOF TEST CATCHING A FEW PERCENT DOES NOT GIVE CLEAR INDICATION OF TROUBLE.



B: TEST FOR 50% FAILURES AT WORKING LOAD + 4σ LEAVES ONLY ONE CHANCE OF FAILURE IN 30,000.

C: DECREASE IN QUALITY SHOWS CLEARLY BEFORE DANGER POINT IS REACHED.

Fig. 14.—Rational Selection of Test Conditions for Reliable Inspection

In this investigation, by controlling the welding conditions and standardizing the conditions of subsequent examination, it became possible to prepare two or more series of specimens, welding first a single piece of one material and then of another, such that each series could be considered, on the average, to be made under essentially the same conditions as the other. Thus controlled, the proportion of the total length of the weld which later cracked became a significant measurement, and it could be consistently shown that a certain heat *S*, considered satisfactory in practice, was always better than another heat *T*, but worse than certain additional heats which were specially processed. However, so long in every sample, after which all steels appeared in the same order after every test and some idea could be gained of their relative quality. The final problem of assigning numerical values to the relative quality of each heat of steel, when tested empirically by all plausible formulas, was shown to conform to a relationship which could be derived from the standard statistical equation, and to no other relationship. The formulas derived for this specific problem are applicable to a wide variety of similar problems.

In the case of the welds, a series welded at one level of severity showed 10% of the weld cracked in steel *S* and 30% cracked in steel *T*. Under more severe conditions, 30% of *S* cracked, but the proportion of

T which cracked was neither 30% + 20% = 50% nor was it 3 × 30% = 90%, but rather the intermediate value of 60%. The *Statistical Index of Quality* which rationalizes these quantities is derived as follows:

Each small portion of the metal to be welded, individual grain or small group of grains, has a certain susceptibility toward cracking, which depends on various factors such as carbon and alloy content, particle size, inclusions present, etc.

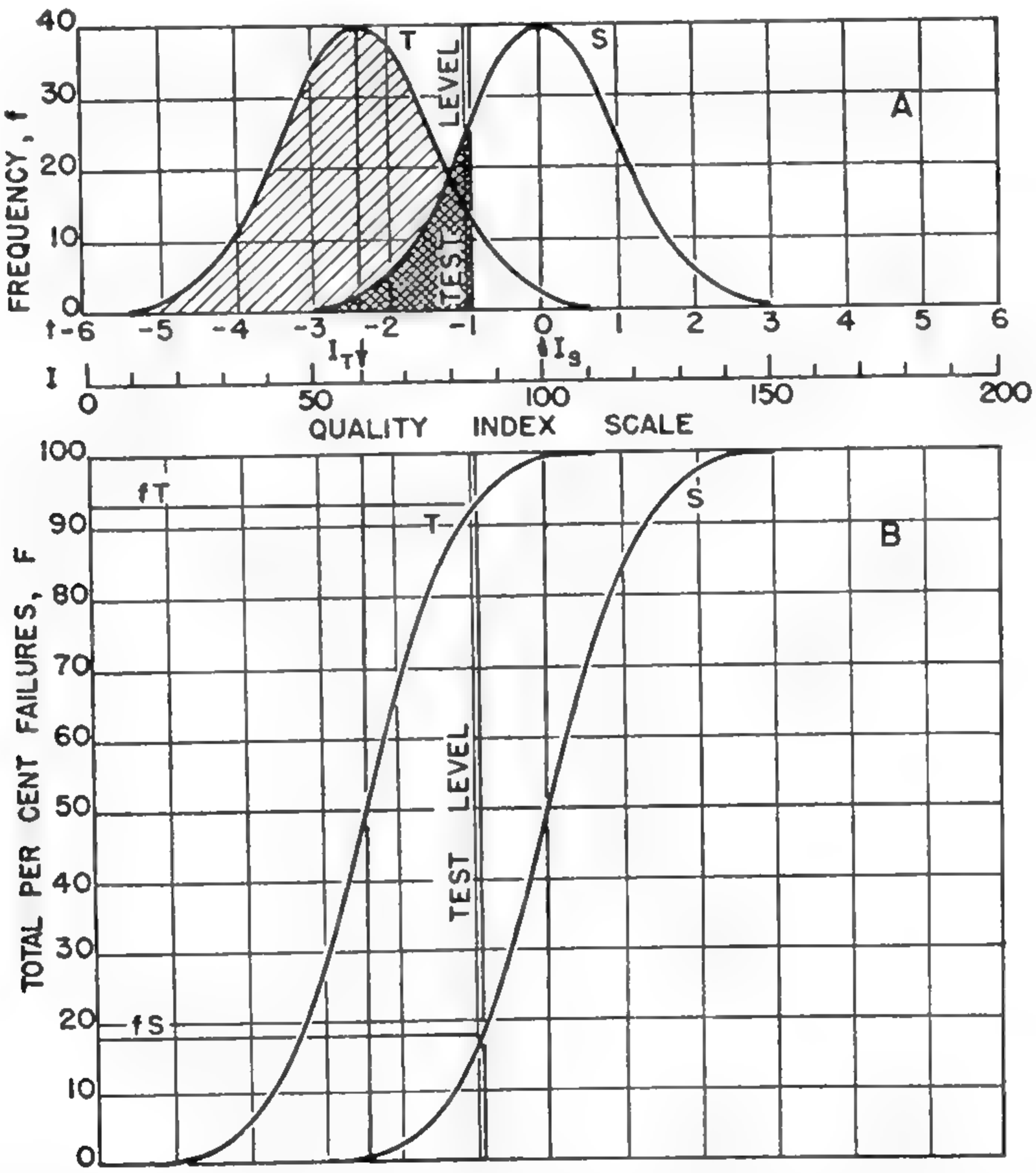


Fig. 15.—Distribution of the Quality of Individual Pieces Within Samples of Two Materials

This susceptibility varies from portion to portion in a random manner, but its average value is a measure of the quality of that particular steel. Each such small portion is exposed to a welding condition of random variability whose instantaneous severity is determined by the temperature, time of exposure, cooling rate, net applied stress, and similar factors and whose average severity throughout the series specifies the *test level*. The interaction of these several factors usually causes the probability of cracking at a specified test level to follow the Gaussian curve quite accurately, and when test conditions are well controlled, causes the standard deviation of this Gaussian curve to be nearly constant. It can be shown, however, that a departure from a normal distribution would not appreciably affect the index value and that a constant standard deviation is not necessary.

To establish an index scale, a quantity of one heat of steel *which has proved satisfactory in practice* is set aside as a standard and arbitrarily assigned an index of 100. It is further agreed that if there is found a steel so poor that there exists a welding condition where *all* (99.87% or more) of the poor steel will crack, while *none* (i.e., less than 0.13%) of this standard steel *S* cracks, this poor steel will be given the index zero. Similarly it is agreed that if there is a steel so good that one welding condition can crack all of *S* and none of this good steel, then this grade shall be

Table 7—Statistical Index of Quality—I_T

S = % failure in the standard material; T = % failure in the material under test.

	S	0	10	20	30	40	50	60	70	80	90	100
T	i	+50	+21	+14	+9	+4	0	−4	−9	−14	−21	−50
00	50	100	129	136	141	146	150	154	159	164	171	200
10	21	71	100	107	113	117	121	126	130	135	143	171
20	14	64	93	100	105	110	114	118	123	126	135	164
30	9	59	87	95	100	105	109	113	117	123	130	159
40	4	54	83	90	96	100	104	108	113	118	126	154
50	0	50	79	86	91	96	100	104	109	114	121	150
60	−4	46	75	82	87	92	96	100	105	110	117	146
70	−9	41	70	77	83	87	91	96	100	105	113	141
80	−14	36	65	72	77	82	86	90	95	100	107	136
90	−21	29	57	65	70	75	79	83	87	93	100	129
100	−50	0	29	36	41	46	50	54	59	64	71	100

Example: When steel S and a proposed substitute T are welded alike under subzero conditions S shows 20% cracking and T shows 90% cracking. The quality index of T, I_T is therefore 65 from the table. If steel S was chosen as one which practically never cracks when welded at room temperature, then it may be predicted that steel T will probably show around 20% cracking if used under the same conditions. It may also be predicted that a steel having an index of about 136 would be needed for practical use at these subzero conditions.

rated 200. From the formulas to follow, the T steel described in a previous paragraph would have an index value of 87.

The conditions obtaining in the various small portions of two steels S and T after completion of a weld test are shown graphically in Fig. 15. In part A of the figure, the two *differential* Gaussian curves each represent a thousand or more individual small portions of one of the steels, as if arranged in piles according to their individual likelihood of cracking at any test level. Thus for steel S, increasing the test level 10% at the scale point $t = 0$ would crack an additional 40% of the individual test units. The curves in Section B similarly show the integrated form of the equation (ogive) where the ordinate shows the total portion cracked at any given test level. The abscissae for both A and B are arbitrary, so chosen that the distribution of failures is strictly normal, and may or may not be proportional to one or more of the physical measurements which might be made of the specimens or of the testing procedure. Abscissa scale t is that generally found in tables of the Gaussian curve, i.e., the number of standard deviations removed from the average value. From the conditions in the previous paragraph, 100 index units = $6t$, giving directly the I or index scale shown.

The manner in which the rating of steel T becomes independent of the test level is apparent from the graph. The number to be assigned measures only the fact that the differential curve peak or mode (50% point of the integrated form) is a certain distance to the left (or bad side) of the corresponding point for the standard steel S. At the arbitrary or accidental level at which the test was made, 18% of steel S failed, as shown by the shaded area under the S curve. From the table to follow, the characteristic point (mode) of the S curve therefore lies 15.3 units (I scale) to the right of the test level. Similarly, steel T shows 93% failure under identical test conditions, hence the characteristic point for this steel lies 24.6 units (I scale) to the left of the test level. Steel T therefore lies 40 units to the left, or bad side of steel S, and as S has been assigned the rating of 100, the index for T is therefore 60, and the position of the test level may be forgotten.

It may readily be seen that the same index value would have been obtained for any test level lying in the region where the two Gaussian curves overlap, i.e., corresponding to index values of 50 to 110, although the proportions which failed would be quite different in each test. The truth of this has been repeatedly demonstrated in practice for the case of hard cracking in arc welds.

Tables 7 and 8 give the values necessary to apply the index calculation to actual experiments. In Table 7, shown mainly for orientation purposes, the percentage failure of the standard material is entered in the top of the table, and of the material to be rated in the left-hand column. The value of the *Statistical Index of Quality, I* is read at the coincidence of these entries. Table 8 gives the information for the calculation of I to greater accuracy, allowing entries for each 1% range of failures. This table

Table 8—Values of Apparent Index, i for 1% Steps (Position of Characteristic Point with Reference to the Test Level)

% Failure	0	1	2	3	4	5	6	7	8	9
0	+50.0	+38.8	+34.2	+31.3	+29.2	+27.4	+25.9	+24.6	+23.6	+22.3
10	+21.4	+20.4	+19.6	+18.8	+18.0	+17.3	+16.6	+15.9	+15.3	+14.6
20	+14.0	+13.4	+12.9	+12.3	+11.8	+11.2	+10.7	+10.2	+9.7	+9.2
30	+8.6	+8.3	+7.8	+7.3	+6.9	+6.4	+6.0	+5.5	+5.1	+4.7
40	+4.2	+3.8	+3.4	+2.9	+2.5	+2.1	+1.7	+1.3	+0.8	+0.4
50	0	−0.4	−0.8	−1.3	−1.7	−2.1	−2.5	−2.9	−3.4	−3.8
60	−4.2	−4.7	−5.1	−5.5	−6.0	−6.4	−6.9	−7.3	−7.8	−8.3
70	−8.6	−9.2	−9.7	−10.2	−10.7	−11.2	−11.8	−12.3	−12.9	−13.4
80	−14.0	−14.6	−15.3	−15.9	−16.6	−17.3	−18.0	−18.8	−19.6	−20.4
90	−21.4	−22.3	−23.6	−24.6	−25.9	−27.4	−29.2	−31.3	−34.2	−38.8
100	−50.0									

Example:

Steel S is rated		100
Steel S cracks 18% under test	i_S =	+15.3
Test level		84.7
Steel T cracks 93% under same test	i_T =	−24.6
Quality index of steel T	I_T =	60.1
or by substitution; $I_T = 100 - (15.3) + (-24.6)$ =		60.1

gives values of i, which is the distance in index units by which the characteristic point lies to the right of the test level. The Index of Quality for steel T is therefore:

$$I_T = 100 - (i_S - i_T) = 100 - i_S + i_T \quad (36)$$

Analysis of numerous ratings for steel tested under a wide range of welding conditions has shown that the standard deviation actually found for the index values is very little greater than the standard deviation which would be predicted for the difference of well-measured physical properties if determined for the same effective number of samples. Analysis of the index values can easily be made graphically on probability paper on which a straight diagonal line covering 10 linear units will give the data of Table 8 directly.

BIBLIOGRAPHY

1. *Probability and Its Engineering*, T. C. Fry, D. Van Nostrand Co., Inc., 1928.
2. *Economic Control of Quality of Manufactured Product*, W. A. Shewhart, D. Van Nostrand Co., Inc., 1931.
3. *An Outline of Probability and Its Uses*, M. C. Holmes, Burgess Publishing Co., 1936.
4. *Index of Statistical Methodology Books and Reviews, 1933 to 1938*, O. K. Buros, Editor, Rutgers University Press, 1938.
5. *Mathematics of Statistics*, J. F. Kenney, D. Van Nostrand Co., Inc., 1939.
6. *Statistical Method from the Viewpoint of Quality Control*, W. E. Shewhart, (W. E. Demig, Editor), Department of Agriculture, 1939.
7. *Applied General Statistics*, Croxton and Cowden, Prentice-Hall, 1939.
8. *Allowable Average in Sampling Inspection*, H. G. Romig, Columbia University, 1939.
9. *Statistical Tables*, H. C. Carver, Editor, Edwards Bros., Inc., 1940.
10. "Mathematical Table" from *Handbook of Chemistry and Physics*, C. D. Hodgman, Editor, Chemical Rubber Publishing Co., 1941.
11. *Engineer's Manual of Statistical Methods*, L. E. Simon, John Wiley & Sons, 1941.
12. *Guide for Quality Control and Control Chart Method of Controlling Quality*, ASA Standards, 1941.
13. *Industrial Statistics*, H. A. Freeman, John Wiley & Sons, 1942.
14. *Poisson's Exponential Binomial Limit*, E. C. Molina, D. Van Nostrand Co., Inc., 1942.
15. *Manual on Presentation of Data Including Supplements A and B*, American Society for Testing Materials, 1943.
16. *Some Observations of Spot Weld Consistency in Aluminum Alloys*, W. F. Hess, R. A. Wyant, R. A. Averbach, NACA, Progress Report No. 13 on Aircraft Spot Welding Research, 1943.
17. *Introduction to Mathematical Statistics*, P. G. Hoel, John Wiley & Sons, 1944.
18. *Sampling Inspection Tables*, H. F. Dodge, H. G. Romig, John Wiley & Sons, 1944.
19. *Quality Control in Aircraft Spot Welding*, N. C. Clark, The Welding Journal, January 1944.
20. *Sequential Analysis of Statistical Data: Applications, SRG 255*, Statistical Research Group, Columbia University Press, 1945.
21. *Determination by Statistical Analysis of Process Minimum for Spot Welding*, H. Robinson, The Welding Journal, May 1945.
22. *Improving the Weldability of High Strength Low Alloy Steels*, S. L. Hoyt, C. E. Sims, N. M. Banta, Iron Age, May 31, June 7 and June 14, 1945; also available in more complete form as Research Project NRC-514, Office of Technical Service, U.S. Dept. of Commerce.
23. *Statistical Quality Control*, E. L. Grant, McGraw-Hill, 1946.
24. *Recommended Practices for Resistance Welding*, American Welding Society, 1946.
25. *Sequential Analysis*, A. Wald, John Wiley & Sons, 1947.
26. *Control Charts*, E. S. Smith, McGraw-Hill, 1947.
27. *Sampling Inspection*, Freeman, Friedman, Mosteller, Wallis, McGraw-Hill, 1948.
28. *Quality Control Methods*, C. W. Kennedy, Prentice-Hall, 1948.
29. *Statistical Department in Heavy Industry*, A. W. Swan, Journal of the Iron and Steel Institute, September 1948.

CHAPTER 45

TRAINING AND QUALIFICATION OF WELDING PERSONNEL*

INTRODUCTION

General Training of Personnel

THIS CHAPTER DEALS with the training of welding personnel. The method of approach is to describe the elements and problems in training and the agencies and methods by which such training is accomplished. Most of the material is presented using the example of arc welding which is no more important than other welding processes, but which probably accounts for a larger amount of the training programs at the present time. Since the method of training for any given process is much the same as for any other, the discussion relating generally to welding training and referring specifically to arc welding, applies also to such processes as oxy-acetylene welding, brazing, carbon arc welding and other commonly used manual welding processes.

The most numerous welding personnel are welders and welding operators. Welding supervisors, foremen, instructors and inspectors usually are drawn from the ranks of both these groups; therefore, the basic training for welders and welding operators is an early and essential part of the training for these higher personnel.

Welding engineers today are very frequently drawn from the ranks of supervisors or inspectors. College-trained engineers usually have a degree in one of the basic engineering fields such as mechanical, electrical or civil engineering, and have acquired an understanding of welding by training or working as a welder, inspector or supervisor.

In this chapter, therefore, the training given to welders will receive most attention and the training for the supervisory or engineering personnel will receive less attention.

Only in more recent years have facilities for properly training welders been generally available. Prior to this, most employers requiring an increase in the number of welders had to do their own training. The need for greater facilities for training has been recognized by both public and private schools. The employer now may choose the best means to obtain, or train, the welders he needs. His choice depends upon the industry, the product, the plant itself and its geographic location and many factors peculiar to welding.

In the first place, the terms welder and welding operator include a wide variety of skills and knowledge. Aside from the obvious distinction between gas-welding, arc-welding and other welding processes, the definition and job specifications vary between one industry and another and even between individual plants in the same industry. In one plant for example, most of the arc-welding work may be positioned and welding performed downhand, using large electrodes and alternating current. A first-class welder with years of experience in such a shop may be of limited value on the ways of a shipyard, where all the welding may be done with direct current and most of it in the vertical and overhead positions. In one plant, gas-welding may be used only on ferrous metals, while in another, only on aluminum, brass or other nonferrous materials. A welder may be skilled in welding thin sheet metal and have no experience in heavy plate fabrication or pipe welding. While many operations within a process have much in common and rest upon the same fundamentals, a man trained only in those fundamentals re-

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quires specific training before he can be a welding operator of value in any plant.

Assuming that an employer has developed job specifications, the first step is to select the best and quickest method to obtain an operator to perform the job. Generally speaking, selection is by one of two general methods or a combination of the two: Training (1) within the plant itself, and (2) by outside schools, either public or private. Figure 1 is a diagram which illustrates and graphically shows the factors in the training of welding operators.

BASIC ELEMENTS OF WELDER TRAINING

General Statement on Qualification of Welding Operators

Since the training program for any welding operator must be based upon the specifications for the work to be done, it is axiomatic that the ability to qualify for (or in other words, to perform) the work must be evaluated in the light of the specifications for the particular job.

It is important to bear in mind that qualification tests determine the *minimum* standard performance of all welders in following a prescribed procedure for making certain welds. However, it must be recognized that mere passing of the minimum requirements for qualification does not in any way guarantee that the man will consistently produce work which meets even the minimum requirements for which he has been qualified.

To have passed the minimum qualification test simply indicates that the man has acquired skill which makes it possible for him to produce acceptable work as compared with a welder who cannot pass the minimum qualification requirements. To have passed these minimum qualification requirements in no way relieves the organization which employs the services of these welders from the responsibility of adequate supervision and quality control, including adequate preparation of the work prior to welding, inspection of the materials and processes prior to welding, furnishing welding equipment and materials of proper quality, adequate procedures for the operation, and the provision for adequate and responsible inspection of the welder's work during and after welding. The responsibility of the employer for additional and special training in procedures peculiar to the product is also clearly implied.

The AMERICAN WELDING SOCIETY's *Tentative Standard Qualification Procedure* (B3.0-41T) recognizes the limitations and implications of the foregoing concept of a standard qualification procedure and within the framework of that concept first points out that "the quality of arc- and gas-welded joints will be determined by the specific welding procedure used and by the ability of the welding operator to apply that procedure." It therefore presents in Part I the method to be pursued in investigating and qualifying a welding procedure, while Part II outlines the method of qualifying welders. Each of the sections provides a comprehensive coverage of its problem to serve as a guide and example in evaluating welding procedures, and qualifying all welders for given procedures, and is an important source of information and guide as to method for any agency or individual interested in training welding operators.

Selection of Trainee

Age.—The range of age may include trainees from the minimum legal employable age to the usual maximum age of employment. The speed with which trainees of various ages learn to weld is about the same. Young men may learn a little faster, but older men do not learn sufficiently slower to make any great economic difference.

Intelligence.—No accepted tests for ability to learn arc welding have been devised, but men who have a higher measurable general intelligence seem to learn more rapidly and are more likely to advance to be higher-rated welders and to the more advanced jobs of supervision.

Physical Conditions.—The prospective welder should be able to pass a standard physical examination, with special attention given to eyesight, respiratory organs and nervous system. In general, he should have a strong physique, since many welding operations require the ability to do relatively heavy work. Sometimes it requires special skills such as working at various heights on straight ladders, board platforms, swing seats, etc. Selection should be made, wherever pos-

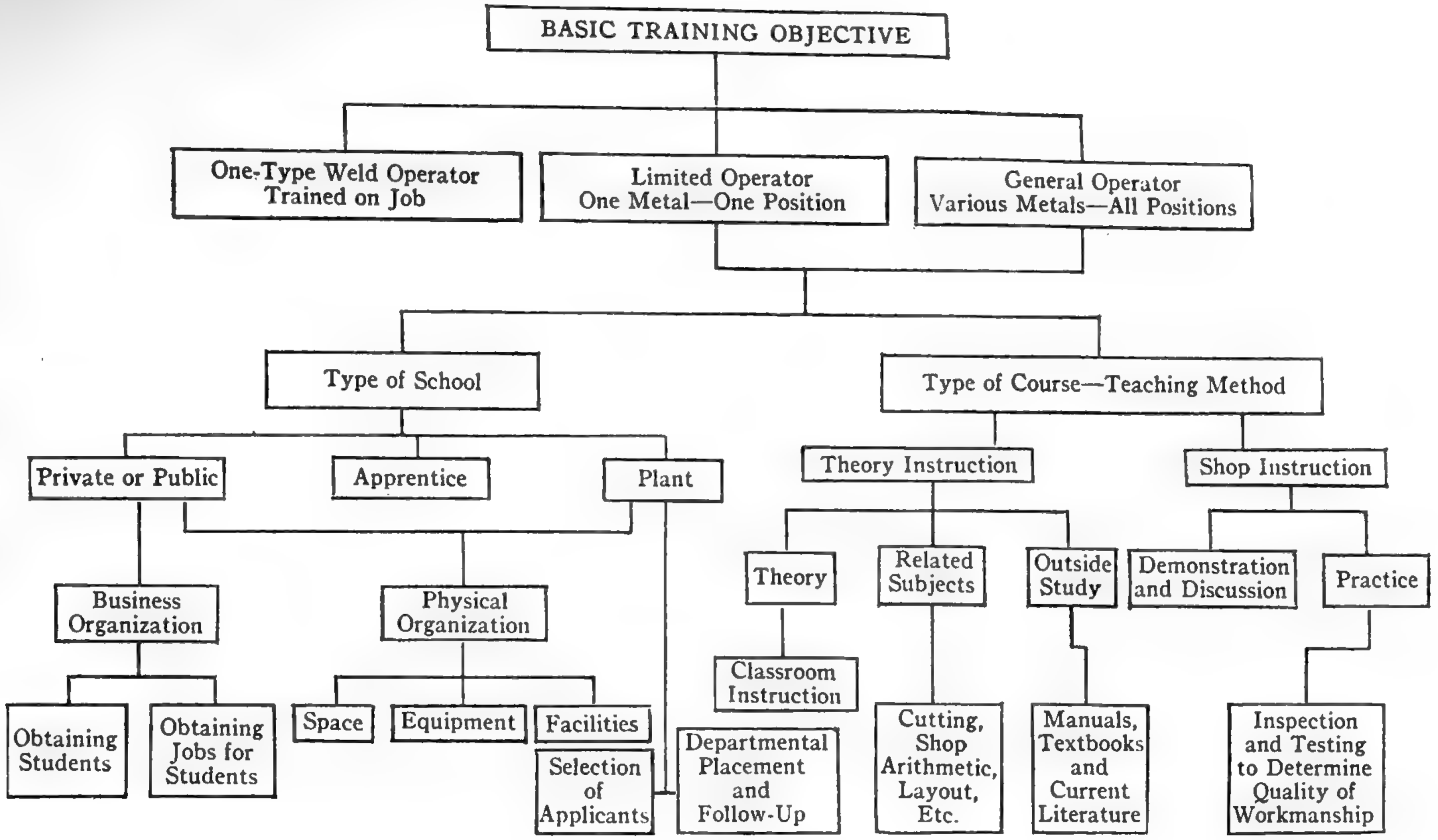

Fig. 1—Factors in the Training of Welding Operators

sible, with due consideration for the requirements of the specific job. Sometimes men must have the agility and ability to get into tight locations and difficult positions to perform the welding operations involved.

Education.—A trainee must be able to read and write and should preferably have a high-school education. He must be interested in welding and must have a desire and a willingness to undergo a period of formal instruction, including manual practice and related theory. For many types of repetitive operation, an elementary education is sufficient.

Equipment for Instruction

Complete units of arc-welding or gas-welding equipment, whichever type of instruction is being given, in good operating condition and moderately current as to type (not obsolete), should be available for each trainee for his individual practice for at least a half day each day during his training period. Adequate space is also an important training requirement.

The usual hand tools, aprons, goggles, gloves and welding hoods should be available. These represent the minimum requirements.

Practice and Instruction Planning

The instruction plan should include three to five hours of manual instruction per day during the entire period of instruction. Manual practice for more than three to five hours per day does not increase the speed of learning. The presentation of the course of instruction must be in such sequence that the student masters the basic skills, such as striking, holding and manipulating an arc, before he can practice depositing welds in the various positions of welding. The deposition of welds in the flat position should precede the vertical and overhead positions, because of the relatively more complicated and difficult manual responses required in the latter positions.

The use of a variety of electrode or welding rod sizes and types and other practice materials, so long as they are closely related to the specific motions and processes being studied, will probably shorten the learning period. Variety in the size and type of welding rods or electrodes and variety in the form of welded joints in a given position add interest to the study, the value of which is reflected in maintaining and encouraging the greater learning speed for the student.

Study of the Theory of Welding

In any welder training program, a study of the basic welding theory as it relates to the manual practice reduces training time and increases the student's value on the future job. A basic study of the nomenclature and definitions for equipment and processes, types of welds, welding positions, etc., aids in understanding and efficiency in the trainee's study.

The use of welder training movies and slide films early in the training program (after the first day or two of practice) has been shown to be very helpful. The repetition of these films two or three times during the training processes has been found to make their use more effective and may be expected to materially reduce the hours of manual practice required.

Examples of different types of welds, joints, electrodes, etc., should be explained as a part of the theory of welding. Elementary blueprint reading should be given to the person who cannot read blueprints. Reading of welding symbols (AMERICAN WELDING SOCIETY *Standard Welding Symbols*) should be taught and the specific type of welding control used on a specific job, if the job for which the welder is being trained is known, should be discussed.

Demonstration by the instructor and explanation of various phases of welding and practice are helpful both during the practice period and in the theory.

A training plan using one hour of a half day for theory and the remaining hours of the same half day for manual practice has been found to be as effective as a full day of practice.

Evaluation and Testing of Students Progress

The proficiency with which a student can deposit the necessary welds is the best test of his progress. During the period of instruction, the instructor, by personal criticism and an analysis of the student's efforts as often as possible provides the student with incentive for effort and the knowledge of how he is progressing in his work. It is helpful and desirable to criticize each new phase of the student's progress, such as types and sizes of

welds from the standpoint of soundness, appearance and ease of deposition. The simple practice of examining a weld, pointing out its defects and breaking it open with a press or sledge hammer provides visual understanding to the student as to how his work is progressing. If specific qualification tests are established for the particular job, the successful performance of those tests by the individual welder can be considered a satisfactory means of evaluating and testing a student's progress. Such tests should be on an individual basis and based upon the minimum requirements of the operations performed by the trainee when he is employed as a production welder.

TRAINING WITHIN INDUSTRY

For training within a plant the employer selects the trainees, provides the space, equipment, materials, instructors, and has complete control over the training methods and subject matter. The minimum requirements of instruction and qualification are coordinated and directed toward the specific requirements of that plant or its separate departments.

The advantages are as follows:

1. Plant standards and methods are impressed on the student from the beginning.
2. The course is designed to cover essential points and methods peculiar to the plant without extraneous material.
3. Much training can be coordinated with production work, and part of the training is done on the job.

The disadvantages are:

1. Space and equipment to be devoted to training are frequently limited.
2. Unless the training program is large, the cost per student is high.
3. The selection of trainees is a major problem and the turnover is frequently high. Determination of aptitude without a fair period of instruction is difficult and much time is lost in proving adaptability.
4. A certain number of graduates on whom much time and money have been expended inevitably drift to other plants.
5. The problem of wages during training hours and occupation during some part of each day is often difficult, since the length of time for which a student can practice effectively is limited to only about four or five hours per day.
6. It is important for plant-trained welders to obtain an all-around welding knowledge and experience. This may be obtained by extension courses after the man is employed as a full-time welder.

Without regard to its advantages or disadvantages, with no other training facilities at hand, training within the plant is frequently the only method available due to the geographical location of the plant. A typical system of the plant method of training arc-welding personnel is that in effect at a midwestern manufacturing plant. This company has found that to start with a man who has had no welding experience and train him is as satisfactory from all points of view as any other way of securing satisfactory welders.

The first step is to hire the man with the definite purpose of training him to weld. Such a man is selected to meet the requirements of mentality, education and character expected of such an employee. He must also pass a rigid physical examination. No experience in welding is especially desired.

After the student welder has been hired, he is instructed in safety practices with special emphasis on the wearing of goggles, protection from arc burn and the care of small burns. The welding instructor then assumes responsibility for him. The first consideration is to familiarize the student with the instructional department and assign a locker to him. The student is then taken to the tool room where tool checks, slagging hammer, electrode stock pot, chipping chisel, and weld gage are issued to him. He then goes to the stock room where he equips himself with safety goggles, welding helmet, gloves, sleeves and apron. The welding instructor assists him in adjusting his equipment to fit and instructs him in such small, but important matters as changing helmet lens cover glasses.

A welding machine is assigned to the student. The instructor explains the care of the cables, holder and machine and has the student start, stop and adjust the machine. Safety precautions are stressed again at this stage. Actual welding practice then is begun. Striking, holding and breaking an arc are first demonstrated by the instructor and then the student tries his hand at it. The next step is to deposit a bead of weld metal in a straight line on a flat plate. Following comes in-

struction in changing electrodes and restarting a weld with emphasis on fusing the new deposit smoothly and soundly to the first deposit. The student is taught from the very beginning to melt his electrodes to a $1^1/_2$-in. stub end which he deposits in a small compartment in his electrode stock pot and later returns to the stock room when he checks out another supply of electrodes.

The theoretical part of the student's training also is begun the first day. He is given his copy of the textbook and a supplementary sheet with a questionnaire covering both the first lesson in the book and the supplementary lesson sheet. The supplementary sheet is designed to teach the student welding requirements presented as symbols on a blueprint. The reading of the textbook and answering of the questions for each lesson are done by the student at home or at the plant, and the questionnaires are corrected by the instructor and handed back to the student as fast as the student turns them in. At least one lesson a week is required under normal circumstances.

Six to eight weeks, depending upon the student, are spent in practice welding under the close supervision of the welding instructor. After he can strike and hold an arc and deposit a uniform, sound bead with one or more breaks and starts in it, the student learns to tack weld pieces and to weld them soundly together. Welding in the flat position comes first. Proper arc length, position of electrode and manipulation of the arc are demonstrated by the instructor and then practiced until mastered by the student. Welds which have been deposited are carefully slagged, brushed, examined and criticized. The effect of porosity, undercut, overlap and excess or lack of heat are demonstrated by pointing out the visible defects and then by actually breaking the weld, so that the student can see what effect various flaws actually have on a welded joint.

More difficult welds are made as soon as the student is skilful enough to undertake them. Multiple-pass, positioned fillet welds acquaint the beginner with the effects of accumulated heat, the need for cleaning of each pass, how much metal can be deposited in one pass with certain sized electrodes and how to get complete fusion, penetration and good appearance.

Horizontal fillet welds are practiced next, with frequent breaking of the specimen welds to demonstrate the need for proper manipulation to obtain good fusion on the perpendicular leg of the weld.

Vertical welds built from the bottom up in one, two or more passes, or down in many passes are made next. Horizontal groove welds, overhead groove and fillet welds are taught last.

Almost all of this practice welding is done on scrap or small sections of plate cut for the purpose, although a few of the more advanced students sometimes weld the more simple joints on an order of factory tote bins or some similar factory equipment. The different types of electrodes commonly used in the shop, their specialized purposes and the characteristics of each under different conditions are learned during practice.

Throughout his entire practice course, and for four to six weeks after welding on production items, the student is studying the theoretical side of his work. The subject matter covers the theory of the welding machine, general terms and names associated with welding, the mechanics of depositing metal by means of an arc, strength of welds and weld metal, bare electrodes and coated electrodes. All of this general theory is correlated with the manual welding practice, first by the welding instructor's personal contact with the student, and next by the supplementary sheets and questionnaire on the lessons.

Some of the later lessons (there are forty questionnaires and three major examinations over sections of the course) are devoted to the use of special welding electrodes, such as for surfacing, special high-tensile electrodes and the welding of special metals. This phase of the course is quite theoretical but forms a basis for the special work which some of the operators do later, and serves to widen the student's knowledge of the possibilities of his craft.

The last eight lessons of the formal study course are devoted entirely to teaching the use of the standard welding symbols. Ordinarily, the student has been welding on the simplest production work in the shop for from one to two months by the time he finishes his course with a final examination on welding and welding symbols.

The step from manual practice in the instruction department to the first pro-

duction job in the shop is an important one. The regular procedure is to go from practice to the welding of simple structures which are positioned for welding and are welded in sufficient numbers to provide a full time job for several new welding operators. The welding is simple, yet has variety in size of weld, thickness of material and length of weld.

The student meets several new factors when he goes from the instructional department to regular welding as a shop operator. For that reason, he is given close attention for a few days by one of the shop instructors. The experience of having his work examined by an inspector is sometimes upsetting to the new welder. Also, as a production welder, the new man is initiated into the experience of working at a productive job and of following specified procedures. The foreman and the welding instructor guide and counsel him.

After three to four months of welding simpler structures the welder is usually placed in a department in which various small structures are fabricated. The work provides a greater variety of welding than simple box sections, and another departmental welding instructor carefully tutors the welder in the new situations which he has to meet.

After four to six months of experience in the small parts welding department, the welder is usually sufficiently skilled to be placed in one of several departments which fabricate the main structures. As one of the welders in these departments, he is usually teamed with an experienced man. Together they set up the structure in a fixture and then weld it in the same fixture, or a special welding fixture which allows for more favorable positioning. This type of work further widens the experience of the welder, by giving him a wider variety of problems. At this stage the new welder really begins to become proficient in the use of the arc as a universal tool for fabrication.

After several months in one or several of these fabricating departments, the average welder has acquired the knowledge and skill which enable him to do most of the ordinary welding which is encountered in the factory. With a short period allowed for his learning the special fixtures for the job, studying the prints and practicing on the job he can usually perform the processes in the normal time and with skill which meets the required standards of quality. Real proficiency, such as the ability to make special setups and welding in all positions without fixtures, requires more practice and experience. At the end of from twenty-four to thirty months his individual preferences, abilities and inclinations tend to direct him toward the place in the organization for which he is best fitted.

TRAINING IN THE VOCATIONAL SCHOOL

Public and private vocational schools have many problems in common, most of them springing from the one major difficulty—the wide variation in job requirements. In order to survive, both must be able to show a record of successful placement in industry.

From the standpoint of industry, the advantages of training outside the plant are as follows:

1. Plant space and equipment are not required purely for instruction.
2. The employer is relieved of the task of selecting trainees and the turnover unavoidably incident to their training. The employer is also saved all or part of the cost of training which may usually be from $200 to $500 per man.

The disadvantages are:

1. The lack of uniformity and standards in training methods.
2. The wide variation in the caliber of instruction prevalent in both public and private schools.
3. There is usually little opportunity to exercise selection in the enrollment of trainees.
4. Although the course may meet an employer's specifications, the graduate lacks shop experience.

In the development of public and private vocational school programs for the training of welders, consideration must be given to (1) relationships to be established between industry and school, (2) selection of those to be trained, (3) modern equipment for school shops and classrooms, (4) organization of a course of study adequate to meet the needs of the field to be served, (5) accurate and reliable instructional material, (6) properly qualified instructors, (7) checking results of instruction and (8) provision for placement of graduates.

High standards in the above eight divi

sions are essential to the success of the program whether the training is of the trade-preparatory type, training boys on all-day trade-preparatory basis for later entrance upon employment in some specialized field; or of the trade-extension type training boys and older men on an evening trade-extension basis for greater efficiency in the work at which they are already employed.

Likewise, both in public and private trade schools, the same basic standards should be maintained.

Relationship Between School and Industry

In the organization and maintenance of programs for the training of welders, desired results can be achieved only when there is a proper relationship between school agencies, employers and labor. In some states the state education law makes mandatory advisory boards for vocational education in all cities and school districts maintaining vocational training programs. Such advisory boards are charged with the responsibility of making surveys to determine the needs for specific types of vocational training, and promoting the establishment of vocational programs in the community.

In small towns and cities, one advisory board representative of industry and labor may meet the need for all industries. In larger cities, subadvisory boards representing each of the major industries are appointed to work under the general direction of the advisory board provided for in the state education law. The importance of maintaining close working relationships between school agencies and industry through such advisory boards cannot be stressed too strongly. The degree of such coordination may mean the difference between complete success and total failure in programs for the training of welding operators.

Selection of Trainees

Choosing a beginner who is to be enrolled in a welding training program is as important as his training. In the guidance of young boys and men of school age into or out of welding training, the schools may be able to effect a selection of trainees conforming generally to the general qualifications stated earlier in this chapter, or specifically for the industrial job which they are to do. Careful selection of those to be trained will also eliminate those who are likely to be poor material because of either physical or mental disabilities.

Course of Study

Courses of study in general welding are justifiable in large industrial areas where job welding shops or large manufacturing plants employ welding mechanics in adequate numbers. In these cases the demand frequently is for welders to do both arc and gas welding. Wherever the numbers to be trained justify it, however, separate classes should be established and separate courses of study provided for adequate training in both arc and gas welding in the several fields—welding for sheet metal workers, welding for auto mechanics, welding for steam fitters, welding for aircraft workers, welding for structural steel workers, welding for factory maintenance men, and the like.

Full-time day courses of study should provide for instruction in shop practice and related technology and in non-vocational subjects. On the basis of a six-hour school day, 30-hour week, 15 hours should be devoted to shop practice and shop theory, $7^1/_2$ hours to related technology—including instruction in applied mathematics, applied science and applied drawing, and $7^1/_2$ hours to non-vocational subjects—including instruction in English, Civics and Industrial History.

For the evening trade-extension type of training program, the most effective course of study can be organized on the basis of short units. Here the purpose is to give instruction supplementary to the daily work of persons over 16 years of age who already are industrial employees.

Instructional Material

New and improved tools and equipment, new processes which have been and are being developed, and the trend toward standardization in procedure make necessary the constant revision of instructional material used in training programs. The instructor who fulfills his responsibility in this regard must be able to revise and write his own job instruction sheets. Much material, however, is available which can be used as basic reference material. The manufacturers of welding equipment and supplies have provided materials and engineering assistance

which can be used to advantage. Some of the trade associations representing industries where the welding process has recently been introduced have developed materials which can be used to very good advantage in their specialized fields. Typical is the *Standard Manual on Pipe Welding* developed and published by the Heating, Piping and Air Conditioning Contractors National Assn. The AMERICAN WELDING SOCIETY's Codes and Standards, particularly the *Code of Minimum Requirements for Instruction of Welding Operators* (Part A—Arc Welding of Steel and Part B-1—Oxy-Acetylene Welding of Steel Aircraft) provide important basic course materials for instruction, described in more detail later.

Another important example of this is the *Outline of Training Course for Oxy-Acetylene Welding and Cutting Operators* issued by the International Acetylene Association. This course presents in outline form a series of self-contained lessons for training welders and cutting operators and inspectors. These lessons have been arranged in the ideal order for presenting a general course in welding, courses in aircraft welding and pipe welding, a general course in cutting, a course for structural steel cutting operators, or a course for inspectors. Each lesson contains an outline of theory or related material to be covered by lecture, suggested assignments for outside study and recommendations for demonstrations and for practice exercises.

Instructional material must be of two kinds: (1) job instruction sheets and (2) related instructional material. Job instruction sheets contain step-by-step procedures in the doing of particular jobs, the listing of the apparatus tools and materials used in each job, together with safety precautions and other suggestions for the instructor and student. Related instructional material provides material and data on welding construction, including the designing, laying out and fabrication of various types of welded joints; engineering and practical data; and specifications and standards covering the welding procedures to be followed in the particular field.

Because carelessness or lack of ability in the proper operation of welding equipment may result in excessive costs and even in hazards to both life and property, it is extremely important that rules and regulations covering safety be incorporated in the instructional material.

Equipping the Welding School

Quarters to be assigned to a welding school depend, of course, on the space which may be available. A shop with a floor area of 1500 sq. ft., preferably about 50 ft. by 30 ft., will prove satisfactory for a welding work room to accommodate a maximum of eighteen students, together with a small lecture room, wash room, a small store room for welding equipment and space for other materials and equipment needed in a welding training program. The floor should be of concrete, if possible. A lecture room may be available for use in another part of the school building. The lecture room should include facilities for the showing of films. Because of the cost involved, many schools prefer to prepare and equip a single room for film work, making it available to all departments in the school.

Experience has shown that effective instruction cannot be given to a group of more than eighteen students by one instructor. If instruction is to be given to larger numbers, the groups should be separated into two or more sections each with its own instructor.

Instructors

The key to the success of the training program is a qualified instructor. A poor instructor, even when provided with the best in equipment, course of study, and instructional material, will produce only mediocre results.

Instructors are of two kinds: Those who teach the practical shop work; and those who teach the related technology—mathematics, science and mechanical drawing. These two types of instructors must possess different training, experience and other qualifications. The instructor who teaches the shop work must be a thoroughly qualified, experienced welder and also he must be a good instructor. The instructor who teaches the related technology must be adequately trained in the applied related subjects and must also be a good instructor. The AWS *Code of Minimum Requirements for Instruction of Welding Operators* mentioned above provides helpful data for instructor evaluation.

Checking Results of Instruction

The knowledge, skill and judgment of pupils should be tested and found satisfactory at regular intervals before new work in the course of study is undertaken. Testing serves three purposes. It determines the progress made by the individual, it acts as a review of the work covered in past instruction, and it shows the instructor where his instruction has been weak in subject matter or in method, or both.

Testing for knowledge and skill involves two distinct operations. Separate tests must be given for each. This is necessary because the student may be well advanced in general knowledge of the welding process and yet have little skill, or vice versa. Although tests for knowledge and skill require separate examinations, the content of each may be related to the other. A performance test may be given which involves the application of principles of the theoretical and technical phases of welding. Performance tests administered at intervals during the course should cover the important skills which have been taught. Tests for knowledge can be oral or written, while tests for skill must be by performance.

The results of these tests furnish a complete history of the student through his entire training period. This history constitutes a record of progress, and should be kept from the time the student is first tested until he has completed his entire period of training. Accurate recording enables the instructor, the student and the prospective employer to know the progress which any student has made.

The above mentioned AWS Code of Minimum Instruction Requirements recommends tests which closely simulate the qualification tests which are used in industry.

Provision for Placement of Graduates

In evening trade-extension programs, students in training usually already have been working as welders. In all-day trade-preparatory training programs, the school and instructor have a definite responsibility to the student for assistance in his satisfactory placement at the conclusion of his training. The record of placement of the school is proof of the effectiveness of the training program. If the right kind of relationship has been established and maintained between school and industry, and if high standards have been maintained, the placement of graduates should follow as a matter of course.

Length of Course

The length of the training period is among the most controversial questions. It should be determined on the basis of need. It is true that a young man with aptitude may be taught in a comparatively short time how to hold an arc and deposit metal. In exceptional cases the metal so deposited will be of good quality. However, it would be ridiculous to say that he is a finished welder. He is good welder material; he is not ready to go to work. He needs many hours of practice so that he can complete basic types of welds. The various manipulation techniques need to be experienced; only through actual practice can he become accustomed to new work positions. The final objective is a measure of the time required to develop the welder to an employable skill.

Under some conditions, there is a tendency for the instructor, or the employer, or the student, to speed up the training program by increasing the length of the shop practice periods. Such procedure is of doubtful value, because when the beginner is kept practicing after he has reached the fatigue point and is working under unaccustomed strain, he is more likely to develop undesirable welding habits than he is to improve his welding ability.

Welding is primarily manual work. Regardless of the desirability that an operator know as much about the theory of his work as possible, the chief function of the welding school is to impart a certain degree of manipulative skill to the student. This skill involves a more or less complete control over the pool of molten metal into which the deposited metal flows under his guidance. When the student can exercise this control without undue tension, and continue it with a uniform measure of skill throughout a normal working day he is ready to go to work.

In areas where there is a great diversity of welding activities, the school management finds it difficult to decide on the scope of the practice exercises. The best solution is to select exercises which are

representative of average conditions, taking care to include enough basic exercises on material of medium thickness so that the student can become thoroughly informed as to the nature of sound weld deposits and how to make them. There is more to be gained by learning to do a small number of exercises well than by a more or less superficial practice over a very wide and confusing range of materials.

When the student is ready to go to work, he is by no means a finished welder. He needs weeks of work under shop conditions to become familiar with the various conditions encountered in practice, which are so widely different from the simple exercises performed in the instruction booth. In many cases the student after graduation is put to work first as a tack welder or on work which is of minor importance. This gives him an opportunity to get further practice under observation, and to observe what the requirements of more advanced work are and to develop his technique until it is satisfactory for the more advanced work. The length of time required for making such progress will always vary from plant to plant.

All of these observations point to the need for cooperation between the employer and the school management. It is usually a simple matter for the employer to arrange with the instructors to provide a certain number of students with any special exercise work that is typical of his plant conditions and operations. It is equally practical to arrange for special qualification tests at the end of the course so that a student who has the necessary aptitude and who has made satisfactory progress during the instruction period can demonstrate at the time of applying for employment that he is qualified to weld on the materials and in the positions which are particularly important for the specific job.

The desirability of instruction in the theory of welding either by classwork or by lectures, making full use of visual aids, can scarcely be questioned. The welder who works with his hands alone is at a disadvantage in competition with one who works with both his hands and his head. Care must also be taken to guard against the possibility of overdoing this type of work at the expense of welding practice. Again the training objective should be the determining factor as to amount of classroom work.

There is a wide divergence in the details of methods used by successful welding schools. Many of them are exclusively devoted to welding instruction and others are departments of larger trade schools. Some of them are better equipped than others. And there is a very great difference in the method of teaching theory. Yet they have some fundamental things in common. They recognize that the most important objective is the development of manipulative skill. They are careful to observe the attitude and aptitude of the student. They familiarize themselves with the requirements of the employers in their area and concentrate on developing the highest possible degree of employability in the students, and they do not certify the student as having satisfactorily completed the course until that student has demonstrated in the school his ability to pass one or more of the recognized qualification tests.

The equipment of the school for practical training should be of ample capacity for practice work for average welding conditions. Welding machines should at least be capable of continuous operation with $^{3}/_{16}$-in. electrodes. In cases where students are being especially trained for employment where larger electrodes are used, the school should have welding machines of sufficient capacity to give this practice. Equipment for the preparation and cutting of metal is essential. Time lost in material preparation will necessarily cut into the practice time and will seriously handicap the trainee.

Fixtures and equipment should be provided for making qualification tests in the school, and the experience of making welds for these qualification tests can well be regarded as a vital part of the instruction rather than as an accessory demonstration. In this connection, it is advisable to have a permanent display board showing samples of welds of different degrees of soundness which have been fractured so as to show the nature of the weld metal.

THE COOPERATIVE PLAN OF SCHOOL AND FACTORY TRAINING

A training program in which a trainee welder must spend roughly half of his time learning or actually welding in

an industry and furthers his general and related education in a formal school on the high-school or college level is known as a cooperative plan, and presents distinct and important advantages. Some of them are:

1. A trainee receives actual practice in real welding work (preferably in periods of not over half a day per day) which develops his manual skill at the most practical rapid rate.

2. Employers of such part time trainees may train them in the specific type of work which is desired and the alternation of students for half a day periods balances their working crews with very little additional supervisory attention.

3. Employers have the opportunity to evaluate the trainees and select those who show the most aptitude and probability of successful operation or advancement.

4. The furthering of the student's general education or related theory in the science of welding or the related mechanical drawing, blueprint reading, mathematics, physics, chemistry, metallurgy and such courses, provides a basis upon which a student may develop a parallel to his shop work for advancement beyond the minimum welder requirements.

5. Employers of these trainees do not have to spend the time and money to provide the related theory and general education which are most desirable for the trainees.

6. The school and the factory management become better acquainted, each learning more about the other's problem and directing his efforts cooperatively toward the common end; that of producing well-qualified welders and welding personnel.

In cooperative training plans, the school and the employing organization work together, each supplying a part of the total training requirements. The employers supply available, part-time training work with pay, as a part of the training and the school furnishes the instruction in pre-employment work and related subjects.

Instructors should be qualified on the type of work that is being covered by the training program. In addition to their ability to weld, they should have had previous experience handling people and organizing work situations. It is often found desirable in the case of training for upgrading taking place in the evening school or where specific training of temporary nature is being carried on to borrow a man from industry to act as instructor.

The training plan should provide for the training of the new employee through pre-employment type of training, for those lesser skill jobs that are so numerous in most shops. After employment a program of upgrading may be set up for the new employee, based upon practical work situations that exist in the particular industry. It has been found best to carry on this training on the student's free time, as this enables him to have a bigger stake in the program and gives the company the opportunity to better evaluate the character of the new employee.

The success of any program will depend to a great extent upon adequate coordination between the school and industry. A coordinator representing the school should work with someone in industry who has the authority to have training policies carried out. It is the job of these coordinators to make sure that the training is meeting the needs of the job and also to provide for a sympathetic acceptance of the new graduate by supervisors and older employees.

Close cooperation between industry and the schools, both public and private, has been emphasized throughout the foregoing. Experience can come only through employment and work on the job. Industry must recognize this fact and in any period in which a shortage of experienced operators exists, accept the partly or school-trained student and through careful supervision, permit him to gain the experience necessary to perform the work assigned. An example of its practical application, both for pre-employment training and in the upgrading of employees, is furnished by the training for welding operators at the plant of a large shipyard on the Atlantic Coast. Certain special circumstances exist in this case which should be given full consideration in evaluating the system and, therefore, the practicability of its application elsewhere:

(a) The shipyard is the largest employer of qualified welders in the district served by the local vocational school. Since this shipyard offers the principal opportunity for placement of students from private schools, it can bring greater pressure to bear upon

their policy than otherwise possible.

(b) There is no production welding in this plant which can be done by students before qualification to the minimum requirements of the United States Navy, except tack welding. The welding time in this is so limited that it provides almost no practice or experience for students beyond familiarizing them with equipment and shop conditions.

For a number of years this company operated its own school within the plant. The disadvantages previously enumerated have been so forcibly demonstrated that a policy of close cooperation with local vocational and private schools was inaugurated for both divisions of its training program; namely, pre-employment training and upgrading. In view of the many facilities now available for pre-employment instruction, both public and private, but with principal dependence upon the latter, the shipyard requires a minimum amount of instruction and the ability to pass the Navy tests before employment. The prospective employee is required to obtain this either at the local vocational school or at his own expense at a private school accredited by the shipyard. Before being admitted for test, the applicant is required to present a certificate or letter from the school certifying that he has completed the minimum instruction course outlined by the yard for tack welding and that, in the opinion of the school, he is ready for the preliminary test, details of which have been made known to all concerned.

Following successful completion of this test, which is given at the plant, the student is offered employment as a welder-learner. As a learner, he performs tack welding on the job during regular working hours but agrees to continue attendance at a welding school designated by the company for a minimum of six hours a week, outside of working hours. Full use is made of the facilities provided by the vocational schools but when these facilities are inadequate for the peak periods of training, learners are sent to private schools at the company's expense. These schools are carefully selected and must meet rigid requirements as to equipment and instructors, and must follow the course of instruction furnished by the shipyard. A traveling inspector spends full time visiting these schools checking on progress of students and maintaining adherence to the terms of the contract.

All instructors must demonstrate their ability to pass all qualification tests required. As a matter of fact, many of the instructors, both full and part-time, at all schools involved, are shipyard welders or subforemen, a number of whom have been furloughed to take full-time teaching positions. Complete records are maintained on each welder-learner and the relative efficiency of instruction at various schools and of various instructors is readily determined. The number of school hours per man to qualify for minimum requirements for Navy work is relatively low although the calendar time, due to only six hours per week of steady welding time, may be unduly long. This can be reduced only by the provision of some form of work during the learner's regular working hours which would provide more welding time than in tacking.

After completion of the advanced course in welding plain and galvanized steel, all types of joints in all positions using $^{3}/_{16}$-in. electrode for vertical and overhead and the larger diameters for downhand work, the learner is given the Navy No. 1 welding tests. Passing these tests terminates his course of instruction in the outside school and establishes his work rating as a third-class welder. From this point on, his upgrading and instruction on special materials is accomplished on the job and by a limited amount of school instruction and practice time within the plant. No method has yet been worked out to obtain adequate instruction elsewhere in special processes frequently involving the use of expensive electrodes and materials not available to schools.

An essential feature of the close cooperation between the company and the schools, both public and private, is the provision of suitable scrap, prepared for instruction. All plate scrap in the plant is assigned to the training program and after being cut into suitable sizes for the use of students, is assigned to the various schools in the approximate ratio of their quota of learners. For those men who have nearly completed the course and are preparing for qualification, regulation test plates are provided for practice, although the official tests are given at the company's plant and are observed by the Navy or other inspection agency involved.

MINIMUM REQUIREMENTS FOR OPERATORS

The American Welding Society Committee on Minimum Requirements of Instructions for Welding Operators has undertaken a broad and comprehensive program of preparing a series of codes of minimum requirements for the several categories of welding encountered industrially. As currently organized this includes (1) arc welding of thick material; (2) arc welding of thin material; (3) gas welding of thick material; (4) gas welding of thin material. The topics under thin materials have been further subdivided to provide for the specific problems encountered in aircraft welding to cover this highly specialized field.

The minimum requirements for candidates for welding courses are dependent, to a large degree, upon conditions existing at the time the course is to be given. Under the exigencies of war-time, it is permissible and sometimes necessary to relax or eliminate requirements which in peace-time are considered essential. However, the policy in writing these codes has been to predicate every feature on normal peace-time conditions and leave adjusting of the details to those administering the code.

Each Part of the Code of Minimum Requirements defines the basic minimum requirements as to equipment and school facilities, qualifications of instructors, hours of practice, hours of related theory, welding exercises and final tests. Each Part also includes a series of appendices containing supplementary information, one of which is an annotated bibliography of publications, books, periodicals, films, etc., of use in training or of interest to the student as a potential welding operator.

TRAINING WELDING SUPERVISORS AND INSPECTORS

In the normal functioning of an organization of welding personnel, the next step in the advancement of a competent welder is to a position of supervisor. It, therefore, follows that a welding supervisor must possess all of the qualifications of a welder, plus the ability to organize work and direct men.

The supervisor should have all the educational background and experience of the welder. Where qualification tests are a regular part of routine, he should be capable of passing them along with his men. He should also be able to perform any of the welding which his men are called upon to execute. A supervisor with such skill will naturally command the respect of those who work for him.

The supervisor must, however, exhibit ability beyond welding skill since it is this added feature which places him in his position of responsibility. He has to organize the work of those under him effectively and efficiently. It is his duty to interpret the policies and program of management in a manner that will be understandable to his force. Another phase of the supervisor's duties is the adjustment of differences between those under him.

The training of a welding supervisor, therefore, is something beyond that of the welder—in fact, much of it is not peculiar to welding. With the background of practical welding the next upward step is training at the level usually classified as foreman training. Further, management must also provide means for acquainting the trainee inspector with their policies and plans.

Advancement in the science of welding may be secured in any of several ways, depending upon the facilities available in the locality. If college level instruction is available it will usually be possible to take evening courses in blueprint reading, elementary metallurgy, elementary strength of materials and other topics related to the day-by-day work. Where college level instruction cannot be secured it is often possible to arrange, through adult education programs in the local high schools, to secure equivalent instruction. Then there is always the possibility of studying many of these subjects through correspondence courses. A further source of welding knowledge which should not be overlooked is membership in the American Welding Society, in conjunction with regular attendance at section meetings, and *The Welding Journal* and other AWS publications which are a wealth of welding information.

The differences between the duties of welding supervisors and welding inspectors are sufficient to justify corresponding differences in their training notwithstanding the fact that many of the subjects

should be given to both groups. While not absolutely essential, a welding inspector should have had some experience in actual welding. Lacking such experience, however, he should receive a very thorough training in the fundamentals of the welding processes to be used on the work to be inspected.

The welding inspector should be trained to read blueprints with great facility. He might well also receive instruction in elementary drafting, particularly the making of field sketches. Obviously he should have a thorough knowledge of the standard welding symbols. Knowledge and skill in the use of tools and instruments employed in making measurements are of prime importance. Similarly he should receive instruction in the standard testing procedures as well as those peculiar to welding. These latter should include visual inspection at all phases of the construction procedure as well as identification of weld defects as disclosed by sectioning, X-ray examination, magnetic particle inspection, etc.

The American Welding Society has published a number of standards for welding in various fields and in addition has certain general standards such as the *Standard Qualification Procedure,* the *Filler Metal Specifications,* etc. A competent welding inspector must be thoroughly familiar with all of these and particularly those applying to the work under inspection. A welding inspector should also be conversant with the welding provisions of such regulations as the ASME *Boiler Construction Code,* the API-ASME *Unfired Pressure Vessel Code* and others.

The duties and function of a welding inspector are well covered in the AWS *Inspection Handbook for Manual Metal-Arc Welding* which covers in detail many of the items discussed briefly here.

TRAINING WELDING ENGINEERS

Welding engineering as a collegiate course leading to the degree of Welding Engineer is taught in only a few schools. In consequence most of the college-educated welding engineers currently in practice have received their training in one of the broad fields of engineering study and subsequently, in industry. Therefore, the first phase of the education of a welding engineer is the acquisition of broad, sound knowledge of engineering, preferably by formal study leading to a degree.

While it is not necessary that an engineer be capable of performing welding operations, it is distinctly helpful to have first-hand knowledge of practical welding. Therefore, one of the next steps is training in the actual welding techniques. Generally, most technical schools provide for some of this instruction, but at best it is insufficient for one who proposes to specialize in the field. The best place to learn the art of welding is in a welding shop.

A fundamental knowledge of electricity, which most engineers receive in school, must be applied and interpreted in terms of welding machines and equipment. This should include not only arc welding but also resistance welding. With modern welding equipment this will include at least an understanding of electronics and if it has not been obtained in the normal college course, will necessitate further study. In a similar manner proper understanding of the gas-welding processes require at least an elementary knowledge of chemistry.

To the training in materials testing which every engineer receives, must be added work in the specialized methods used in weld testing. However, this is but one phase of the large field of inspection of welding and the codes under which such inspection is conducted. The welding engineer should have a knowledge of all the codes and specifications used in welding and be thoroughly familiar with those used in daily work. Since the welding engineer supervises the work of the welding inspector, his knowledge must be at least equal to that of the inspector in order that he may be able to direct his work intelligently.

Metallurgy is another important phase of the welding engineer's education. It should include a thorough training in the fundamentals and may be a part of the basic course in engineering, or it may be taken as supplementary work. The fundamentals, however, must be expanded to cover the application of this very important subject to the specific problems encountered in welding. The program in this field should include ferrous and nonferrous metallurgy. It should also treat the functions and uses of electrode coatings, fluxes, inert gases and, in short,

anything which influences the composition, soundness or quality of the weld.

It may be assumed that an engineering graduate will have had a thorough grounding in design fundamentals. This training should be supplemented with specific instruction in welded design. The welding engineer should be the last resort on matters related to welding. Therefore, it follows that his education and training should be broad so that he may be able to render mature decisions.

BIBLIOGRAPHY

1. *Tests for the Selection of Welding Operators,* International Acetylene Association, 1940.
2. *Training of Welding Operators,* Air reduction Sales Company (set of four) Oxy-Acetylene Instruction Course (Lectures) 1942; Oxy-Acetylene Instruction Course (Exercises), 1942; Arc Welding Instruction Course (Lectures), 1940.
3. *Standard Qualification Procedure,* American Welding Society, 1941.
4. *Engineering Essential for Welders,* H. M. Priest, American Welding Society, 1942.
5. *The Instructor of Steel Arc Welding,* W R. Stunnard, 1943.
6. *Theory and Practice of Arc Welding,* R J. Sacks, D. Van Nostrand Co., 1943.
7. *Arc Welding Engineering and Production Control,* W. J. Brooking, McGraw-Hill, 1944.
8. *Code of Minimum Requirements for Instruction of Welding Operators: Part B-1—Oxy-Acetylene Welding of Steel Aircraft (Tentative),* American Welding Society, 1944.
9. *Code of Minimum Requirements for Instruction of Welding Operators: Part A—Arc Welding of Steel,* American Welding Society, 1945.
10. *Inspection Handbook for Manual Metal-Arc Welding (Emergency Standard)* American Welding Society, 1945.
11. *Procedure Handbook of Arc Welding Design and Practice,* Lincoln Electric Company, Eighth Edition (1945).
12. *Training Oxy-Acetylene Welding and Cutting Operators,* Instructors Outline, International Acetylene Association, 1946.
13. *Interpreting Teaching of Arc Welding from an Analysis of Motor Learning Studies,* W. J. Brooking, The Welding Journal, November 1947
14. *Lessons in Arc Welding,* The Lincoln Electric Co., 1947.
15. *The Welding Encyclopedia,* T. B. Jefferson Editor, The Welding Engineer Publishing Co., Twelfth Edition, 1947.

CHAPTER 46

SAFE PRACTICES IN WELDING AND CUTTING*

GENERAL

IT IS NOT INTENDED that this chapter go into the question of what structures can be welded safely beyond stating that where the safety of a structure is dependent upon the strength of the welded joint, the welding shall be carried out under the provisions of the code which applies and that the procedure and operators doing the work shall be qualified in accordance with the provisions of the applicable code.

Manufacturers furnish instructions with their equipment and supplies; the user should be conversant with these. The handling, storage and use of equipment and supplies for all welding and cutting operations require that the user familiarize himself with and observe the safe practices given herein. Further details will be found in the sources listed in the bibliography at the end of this chapter.

SELECTION AND INSTALLATION OF EQUIPMENT

General

It is necessary not only to select the welding equipment and materials which will give a satisfactory finished product but it is also important to determine that the materials and equipment can be used safely under the conditions required by the operation.

Welding equipment and apparatus are manufactured in different sizes and, therefore, this factor should be given consideration when securing tools from the storeroom or making purchases.

Having selected the proper equipment, users should familiarize themselves with its proper use as noted in the manufacturer's literature.

Gas-Welding and Cutting Equipment

It is important that only apparatus, such as torches, regulators or reducing valves and acetylene generators, that have been examined and tested and found to be safeguarded in so far as is practicable, be used. Most insurance companies and local authorities will accept materials listed by Underwriters' Laboratories, Inc., Chicago, or approved and listed by Factory Mutual Laboratories, Boston. The proper welding head or mixer, tip or cutting nozzle should be selected according to the chart or table furnished by the torch manufacturer.

Only acetylene generators manufactured in accordance with approved standards of construction and plainly marked with the maximum rate in cubic feet per hour of acetylene for which they are designed, weight and size of carbide necessary for a single charge, the manufacturer's name and address and the name or number of the type of generator should be used.

Hose and Hose Connections.—Hose necessary to connect a torch or other welding device to gas-supply outlets must be of a good quality of rubber having a sufficient number of plies of fabric to withstand the service for which it is employed. Red is the generally recognized color for fuel-gas hose and green for oxygen hose.

Hose connections should conform to *Standard Hose Connection Specifications* of the International Acetylene Association. They should be marked for identification to avoid interchange of fuel gas

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* Prepared by a committee consisting of H. F. Reinhard, International Acetylene Association, *Chairman*; A. G. Cranch, Union Carbide & Carbon Corp.; R. S. Donald, R. S. Donald, Inc.; F. O. Gaskill, The Linde Air Products Co.; W. W. Reddie, Westinghouse Electric Corp.; F. C. Saacke, Air Reduction Sales Co.; E. Vom Steeg, General Electric Co.; B. L. Vosburgh, General Electric Co.

and oxygen hose. Hose connections must be made through substantial fittings and clamped or otherwise securely fastened in such a manner as to withstand without leakage, a pressure twice as great as the maximum delivery pressure of the pressure regulators provided on the system. The connections between hose and nipple or gland may be of either the ferrule or clamp type.

A single hose having more than one gas passage is not recommended if a wall failure would permit the flow of one gas into the other gas passage. Hose with an external metallic covering is not recommended. However, in certain types of operations, particularly machine processes, hose having an inner metallic reinforcement which is neither exposed to the gas passage nor to the outside atmosphere is acceptable. Short lengths of metal covered hose which are a part of the machine or appliance are acceptable.

While in some classes of light work it is desirable to have a light and flexible hose, such hose must be capable of withstanding a hydrostatic pressure of 200 psi. held for 5 minutes. For heavier service and for gases under pressures greater than 15 psi., a hose capable of withstanding a test pressure of 400 psi. shall be used.

Cylinders.—Only cylinders which comply with the specifications of the Interstate Commerce Commission, effective at the date of their manufacture, shall be used for the storage and shipment of compressed gases. Such cylinders must be maintained and charged with gas in accordance with ICC regulations.

Manifolding Cylinders.—Cylinders are manifolded for the purpose of centralizing the gas supply, to provide a continuous supply of gas and to provide gas at a rate in excess of that which may be obtained from a single cylinder. Such manifolds must be of substantial construction and of a design and material suitable for the particular gas and service for which they are to be used. The wide range of pressures encountered in the gases used, from the relatively low pressures of acetylene to the high pressures needed for oxygen, makes it necessary that care be employed in the construction, installation and maintenance of manifolds. It is advisable to obtain manifolds from, and have them installed under the supervision of those familiar with the proper practices with reference to their construction and use.

Regulators.—Regulators or automatic reducing valves shall only be used for the gas for which they are intended.

Arc Welding Equipment

Machines.—Arc welding machines may be designed for use with either direct current or alternating current. Direct current machines consist of a generator with ampere and voltage characteristics suitable for arc initiation and maintenance, driven by a motor, or, for locations where electric power is not available, by either a gasoline or Diesel engine.

Alternating current machines are of the two-winding, air-cooled transformer type with secondary (output) characteristics suitable for initiating and maintaining the arc.

The National Electrical Manufacturers Association has, over a period of years, developed standards for electric arc-welding machines and kept these up to date as new developments or practices became established. These standards cover established practice in ratings, basis of rating, methods of test and broad overall principles of construction contributing to safety.

The NEMA Standards referred to establish the industrial ratings of arc welders, both a.c. and d.c., on the basis of 60- and 50%-duty cycles. In the case of a.c. transformer-type welders, a third class is added, which is known as the limited input welding machine.

The 60%-duty cycle machines covering ratings 200 amp. and over are usually heavy duty welders. The 50%-duty cycle machines, having ratings 200 amp. and below, are intended for lighter welding operations, which usually do not involve continuous welding.

The limited input machines are primarily for use on single-phase circuits of limited capacity such as are found serving small shops, service garages and farms.

The 50%-duty cycle and limited input welders are essentially portable machines in that they are not used in a fixed location nor, in general, in a fixed area. Consequently, standard practice is to provide these machines with primary service

cable and fittings and with complete sets of welding accessories. Further, since they are generally used in locations and in shops where expert supervision is not available, they are usually listed by the Underwriters' Laboratories, Inc. Direct and alternating current machines in the 60%-duty cycle class usually are used in industries where good supervision of installation and operation is available; consequently, these machines are not listed by the Underwriters' Laboratories.

Installation of Equipment.—The 1947 edition of the *National Electrical Code* covers the proper installation procedures for power supply circuits and circuit protection for both d.c. motor driven and transformer type a.c. welding installations.

It should be kept in mind that any device mounted on an a.c. welding machine should be capable of opening the circuit under any conditions of load. Contactors are not generally used because they are not circuit breakers. The *National Electrical Code* covers the proper selection of breakers or switches for the duty required.

Provision must be made in all cases, for both a.c. and d.c. machines, for grounding the frame or case of the machine, in order to protect the welder against the possibility of exposure to the power supply voltage due to possible breakdown of insulation in the machine. Although this is improbable in modern machines, this safety measure should always be observed.

Grounding of the frames is quite easy in machines permanently installed, but can be easily overlooked in portable machines. The use of multi-conductor primary cables is recommended. In the case of small, portable, single-phase a.c. machines an Underwriters' Laboratories approved primary cable, with two power conductors and one ground conductor complete with primary fittings, is usually supplied as a part of the machine.

Attention is especially called to the following practice, which should be used in the installation of groups of single-phase, transformer-type machines on single-phase or poly-phase systems.

Although most modern a.c. welding machines have open-circuit voltages within the maximum 80 volts recommended in the NEMA Standards, indiscriminate connection of these machines without attention to polarity and phase relations of the individual machines can result in combinations of voltages which under possible, even if remote, circumstances could expose the operator to a considerably higher open-circuit voltage. The American Standard on *Safety in Electric and Gas Welding and Cutting Operations* contains explicit instructions on how to handle this problem.

Accessories and Cables.—The welding circuit, consisting of welding-service cable for the electrode lead and work lead, electrode holder, ground clamps and connectors for providing extensions to the leads are among the accessories required for arc welding.

Electrode Holders.—Electrode holders of many individual designs are available for the lightest to the heaviest types of welding. These holders broadly fall into two classes: holders which are fully insulated and those which are insulated except for the electrode gripping jaws.

Many bare jaw holders are still used but the trend is toward the fully insulated type. The fully insulated type should always be used with a.c. machines to afford additional welder protection. Care should be taken to make sure that fully insulated holders do not have exposed screw heads on any portion of the holder that might come in contact with the operator.

A continuous length of cable should be used from the holder to the machine, thus avoiding joints which, if not well insulated, could come in contact with the operator. This is usually satisfactory if lengths do not exceed 35 ft. and a good grade of extra flexible welding cable is used. In no case should cable splices be permitted within 10 ft. of the holder.

Cables and Welding Leads.—Welding cables have been developed to meet requirements of flexibility and hard usage and only cable of this type should be used, and of a capacity to meet the maximum current requirements of the job. Cable sizes for usual welding operations are given in Table 1.

When welding lead cable extensions are necessary, substantial insulated connectors of the locking type should be used.

The work lead (cable) is the most satisfactory means of providing the return circuit (ground) from the work to the

welding machine. Some operating conditions may require using a steel structure or pipe line for the return circuit. Under such circumstances, precautions must be taken against creating unsafe conditions. Pipes carrying gases, flammable liquids or electrical conductors, should never be used for ground returns.

Table 1—Recommended Cable Sizes

Welding Current, Amp.	Cable Size, No.
100	4
150	3
200	2
250 to 300	1/0
300 to 450	2/0
500	3/0
600	4/0

Pipes or structures used for ground returns should have all joints checked to make sure there is no sparking or heating that could constitute a fire hazard. Joints should be bonded if such structures are to be permanently used, and periodic inspections should be made to insure that no condition of electrolysis or fire hazard exists due to using these structures as conductors.

FIRE PREVENTION

General

Fires at or near welding operations are nearly always due to carelessness and, being preventable, should be eliminated. Fires rarely occur where welding equipment is set up for production work because reasonable safeguards are built into the setup. It has been found that the majority of fires occur from portable equipment but these fires can also be prevented by proper precautions.

Certain definite rules for the prevention of fires when welding and cutting have been formulated as follows:

Cutting or welding should not be done where an open flame or arc would be dangerous, as in or near rooms containing flammable vapors, flammable liquids, lint, flammable dust or exposed loose combustible material.

Be sure that welding or cutting equipment is not used near dipping or spraying rooms or rooms containing loose readily combustible material unless there is no possibility of the vapors or the sparks or molten metal passing through broken or open windows, open doorways or cracks or holes in walls or floors.

Do welding and cutting in a safe rather than a hazardous place if the work can be moved.

Where welding or cutting must be done near combustible material, take special precautions to make certain that the sparks or hot slag, from cutting operations particularly, do not come in contact with combustible material and thus start a fire. Move exposed combustible material a safe distance away, say 30 or 40 ft. if the work to be welded or cut cannot be moved. Sweep floors clean and, if combustible, wet them down before starting work. Preferably, cover wooden floors with metal or other suitable noncombustible material where sparks or hot metal are likely to fall. Whenever there are floor openings or cracks in the flooring, make certain that there are no highly combustible materials on the floor below, where they would be exposed to hot metal or slag which might drop through the floor. Take particular attention to see that no hot slag or sparks fall into machine tool pits and that no openings exist beneath the protective curtain through which hot slag might escape and roll along the floor.

Observe the same precautions outlined in the above paragraph with regard to cracks or holes in walls, open doorways and open or broken windows. Use sheet metal guards, asbestos curtains or other fireproofing where needed. Make sure that the guards and curtains give complete protection.

When it is necessary to do welding or cutting close to wooden construction, or in locations where combustible material cannot be removed or protected, fire-extinguishing equipment should be provided suitable for the type of fire that may be encountered.

Whenever combustible material has been exposed to molten metal or hot slag from cutting operations, keep a man at the source of the work for a half hour after completion, to make sure that smoldering fires have not been started.

Arc and Resistance Welding

In addition to the general recommendations given above, the usual care and inspection of electrical circuits should be

provided for the primary circuits of arc or resistance welding machines.

In the case of arc-welding machines practices which could lead to overheating or short circuiting of the welding leads with attendant fire hazard, such as use of undersize cable, allowing cut or worn cable or joints to go unrepaired, or carelessly throwing down electrode holders when not in use, should be eliminated.

Gas Welding and Cutting

All gas-welding and cutting equipment should be kept in good order. Good hose should be used and renewed when necessary. If hose is worn near the couplings, a few inches should be cut off and the connections renewed making sure that they are tight. Good connections between regulators and cylinder valves are important. Torches should never be hung from regulators or across the tops of cylinders.

Thermit Welding

In thermit welding the mold should be thoroughly dried before the charge is lighted. The crucible should always be provided with a cover. When the charge has been ignited the operator should stand a few steps away and should wear goggles. Painful burns may occur from the metal splashings, by upsetting the crucible, by the breaking of the mold, or by allowing the molten metal to come into contact with moisture in the mold, on the floor or on the ground.

ACCIDENT PREVENTION

General

Members of the welding industry are leaders in the important campaign to reduce accidents. Cooperation between the industry and organizations in the fields of fire prevention and accident prevention has resulted in apparatus with built-in safeguards in so far as it is practicable. The use of common sense and the precautions recommended below will further the reduction of accidents. Because of their importance, certain points mentioned elsewhere are repeated.

Never support welding or cutting work on compressed gas cylinders or other containers.

Never do welding or cutting in the presence of flammable gases or vapors. Do not weld or oxygen cut an oil barrel or container that has held flammable liquids, vapors or other flammable materials, without first making sure that such materials have been completely removed.

A room where welding or cutting is to be performed must be well ventilated; strong drafts directed at the welding work, however, should be avoided.

Never attempt to preheat or weld jacketed vessels, tanks or containers or cored or other hollow parts until after every possible precaution has been taken to sufficiently vent the confined air. A metal part which is suspiciously light is hollow inside, and an opening should be drilled before heating; otherwise it may act like a bomb.

Never lay work that is to be heated or welded on a concrete floor because when sufficiently heated a portion of the concrete may spall and fly with possibly injury to the operator.

All mechanical power transmission apparatus such as gears, shaftings, coupling, clutches, etc., exposed to hazardous contact should be guarded.

If it is necessary to work on scaffolds, platforms or runways, adequate provision should be made to prevent falling. This can be accomplished by the use of railings, safety belts and life lines, or some other equally effective safeguard.

If welding is performed in confined spaces, and a welder must enter through a manhole or other small opening, some means should be provided for quickly removing him in case of emergency. Safety belts and life lines used for this purpose should be so attached to the welder's body that his body cannot jam in small exit openings.

Before operations are started, heavy portable equipment mounted on wheels should be securely blocked to prevent accidental movement.

Arc Welding

In case internal-combustion, engine-powered electric generators are used inside buildings or confined areas, extreme care must be exercised to conduct the engine exhaust to the outside atmosphere.

Welding leads and primary power supply cables should be kept clear of ladders, passageways or doors. Keep cables used for power service to portable machines and welding leads out of places

where there is possibility of machines or trucks running over them.

Repair or replace defective cable immediately. Use insulated cable connectors of the locking joint type, having a capacity no less than the capacity of the cable. Disconnect power before splicing any cable.

Do not allow power supply cable used for portable welding machines to become tangled with the welding cables or to be near enough to the welding operation to sustain possible damage to the insulation from sparks or hot metal.

Do not weld without all electrical connections, power supply, welding leads, holder and ground clamp being secure and the welding machine frame well grounded. .The work clamp must be securely attached to work before any welding is carried on. Where practical, sufficient permanent outlets should be installed so that it will not be necessary to have extensive cables strewn about.

Disconnect welding machines from power supply when they will be left unattended.

Welding cables should be kept dry and free from grease and oil. They should be arranged in such a manner that they do not lie in water or oil, in ditches or on bottoms of tanks.

The practice of dipping hot electrode holders in water should be prohibited.

Power cable receptacles for portable welding machines should be arranged so that it is impossible to remove the plug without opening the power supply switch, or use plugs and receptacles which have been approved to break full load circuits of the welding machine.

The open-circuit voltages, either a.c. or d.c., required for satisfactory welding are low by comparison with voltages used on lighting circuits or other portable industrial tools and normally neither will cause injury or severe shock. The fact that they are low may and does lead to carelessness; consequently, welders should be carefully instructed on how to avoid shock. The danger is particularly present in hot weather, when the welder is sweaty, or when he is wet. He should develop the habit of always keeping his body insulated from both the work and the metal electrode and the holder, and should avoid standing on wet floors or coming into contact with a grounded surface. Particularly, he should never permit the bare metal part of an electrode, the electrode insulation or any metal part of the electrode holder to touch either his bare skin or any wet covering on his body. Consistent use of well-insulated electrode holders and cables, dry protective coverings on the hands and body and insulation from ground will be helpful in avoiding contact.

Partially used electrodes should be removed from holders when not in use. The welder should have a place to lay down his holder or hang it up when not in use in a manner that will avoid contact with persons or conducting objects.

All welders should further be instructed in checking their equipment to make sure that electrode connections and insulation on holders and cables are in good condition.

In the interests of safety, the NEMA standards establish the maximum open-circuit voltage for industrial a.c. welding machines at 80 volts for manual welding and 100 volts for machine welding. The ASA Code previously referred to specifies 100 volts for single-operator, d.c. machines, 80 volts for a.c. machines when used on manual welding and 100 volts for a.c. machines used on machine welding as the maximum open circuit voltages.

The above figures are rms. values and are not set as safe values but as maximum values, which need not be exceeded in good welding practice with all types of commercial electrodes. In fact, some types of electrodes are very satisfactory for operating at much lower open-circuit voltages and some machines are so designed as to operate with any type of electrode at open-circuit voltages substantially lower than these values.

Automatic open-circuit voltage controls, which automatically reduce the open-circuit voltage to approximately 30 volts may be provided for a.c. machines used in outdoor work where welders may be working on wet steel where it is hard to keep dry, or for use in confined quarters where there may be greater probability of the welder getting across the open-circuit voltage due to restricted space.

Resistance Welding

Flash welding installations should be equipped with metal shields to protect

operators and other workers from flying molten metal.

Gas Welding and Cutting

Those in charge of acetylene generators, acetylene or oxygen piping systems, or oxygen or acetylene manifolds should be instructed carefully and judged competent for this work before being placed in charge. Printed rules and instructions covering the operation, maintenance and handling of acetylene generators, compressed gas cylinders and manifolds are generally supplied, on request, by the manufacturers and must be strictly followed. Precautions against freezing in cold weather should be observed.

Always refer to a gas by its correct name. Technically both oxygen and acetylene are gases but they must be handled differently; therefore when oxygen is wanted ask for it by its name, *oxygen*. Likewise ask for *acetylene* when this gas is needed. Oxygen and acetylene have been used as examples, but remember that every gas used should be referred to by its correct name. Liquid acetylene should never be used.

Generation, distribution through hose or piping or utilization of acetylene at a pressure in excess of 15 psi. gage pressure is prohibited. This does not apply to acetylene in a suitable solvent in Interstate Commerce Commission specification cylinders.

Use only approved generators and apparatus. Many accidents have been caused by the use of home-made generators and other substandard equipment. The total hourly output of an acetylene generator should not exceed the rate for which it is approved and marked.

Mixtures of acetylene with air or oxygen may be explosive and must be carefully avoided. No device or attachment facilitating or permitting the mixture of air or oxygen with acetylene prior to consumption, except at the burner or in a standard torch, should be used unless specifically approved for the purpose.

An approved hydraulic back-pressure valve must be provided as a part of every generator installation. These valves require regular inspection at frequent intervals to see that they are properly filled with water.

As oxygen under high pressure may react violently with oil or grease, every possible precaution should be taken to prevent oxygen from coming into contact with oil or grease. Oxygen cylinders, valves, regulators, hose and other apparatus and fittings must be kept free from oil or grease, and should not be handled with oily hands, gloves or greasy equipment.

Under no circumstances should acetylene be brought in contact with unalloyed copper except in a torch tip or nozzle.

Cylinders not provided with fixed handwheel valves should have keys or handles on valve spindles or stems while cylinders are in service.

Oxygen or acetylene should never be used directly from a cylinder or cylinder manifold without reducing the pressure through a suitable pressure regulator.

Pressure-adjusting screws on regulators should always be fully released before the regulator is attached to a cylinder and the cylinder valve opened. The valves on cylinders should always be opened slowly. Stand to one side, never in front, of pressure-regulator gage faces when opening cylinder valves.

Oxygen and acetylene cylinders and portable acetylene generators should be placed far enough away from the welding position that they will not be unduly heated by radiation from heated materials, by sparks or slag or by misdirection of the torch flame.

Transferring gas from one cylinder to another or mixing gases in a cylinder, should never be attempted by other than regular gas suppliers. Do not use a cylinder in a setup where it may be possible for foreign gases or substances to be drawn or blown into it.

Compressed gas cylinders and other high-pressure containers should always be handled carefully. Valve-protecting caps, when supplied, should always be kept in place and handtight except when cylinders are in use. Knocks, falls or rough handling may damage cylinders, valves or fuse plugs, and cause leakage or accidents.

When cylinders must be handled by a crane or derrick, they should be carried in a cradle rather than in a sling, and extreme care should be exercised so that they are not dropped. Under no circumstances should cylinders be lifted with electromagnets.

If cylinders are used above the ground

or floor level, as on cranes or roofs, they should be securely lashed to railings or other stable objects.

Empty cylinders should be plainly marked *Empty* or *MT* and the valves should always be closed.

All cylinders should be protected against excessive rise in temperature. Cylinders may be stored in the open, but in such case should be protected against extremes of weather. During winter, cylinders stored in the open should be protected against the accumulation of ice and snow; in summer, cylinders stored in the open should be screened against the continuous direct rays of the sun in localities where high temperatures prevail.

Recessed tops of cylinders should not be used as resting places for tools or other articles, nor filled with water as this may damage the valves and safety devices and thus nullify the protection given by safety devices.

Where acetylene is supplied through a piping system, torches should not be operated while the source of acetylene to piping system is shut off.

Welders should always follow the instructions issued by the manufacturer of the apparatus in use, regarding the sequence of operations in lighting, adjusting and extinguishing torch flames, and connecting the apparatus to the sources of gas supply. This is especially important in lighting torches, the procedure for which varies with the design and style of torch employed.

If, when the valve on the acetylene cylinder is opened, there is found to be a leak of acetylene around the valve stem, close the valve and tighten the gland nut. If this does not stop the leak discontinue the use of the cylinder and remove it to the out-of-doors. In case the acetylene should leak from the cylinder valve, and cannot be shut off with the valve stem, remove the cylinder to the open.

If a leak of acetylene should develop at a cylinder fuse plug, remove the cylinder to the out-of-doors well away from any source of ignition, open the cylinder valve slightly and allow the acetylene to escape slowly. A warning should be placed near this cylinder not to approach it with a lighted cigarette or other source of ignition. A regulator may be attached to a leaky valve to stop leakage temporarily. Tag leaking cylinders plainly, promptly notify the supplier, and follow his instructions as to their return.

Never tamper with nor attempt to repair oxygen cylinder valves. If trouble is experienced, promptly send the supplier a report on the character of the trouble, giving serial number stamped on the cylinder. Follow his instructions as to its prompt return.

Oxygen should never be used to ventilate a confined space. Oxygen is not combustible but it accelerates combustion. In an oxygen-enriched atmosphere, clothing and other combustible material will ignite readily and burn fiercely.

Under no circumstances should more than one charge of carbide, even a small part of an extra charge, be run into one charge of water in an acetylene generator.

A jet of oxygen should never be permitted to enter a fuel oil or storage tank that has contained a flammable substance.

A serious accident may easily result if oxygen is used as a substitute for compressed air. Never use oxygen in pneumatic tools, in oil preheating burners, to start internal combustion engines, to blow out pipe lines, to dust clothing or work, to create pressure or for ventilation.

EYE PROTECTION

In welding or cutting applications it is very important that the eyes be protected from the heat and glare of the flame or arc, and from the particles of hot metal that may fly up from the work. Properly designed and colored lenses fitted in suitable goggles will furnish adequate protection to the eyes of gas welders and cutters. In arc welding, it is necessary for welders to be equipped with shields or helmets that will protect not only the eyes but the skin because of the intensity of the ultra-violet and infra-red rays. The arc should not be struck without having such helmet or shield over the face.

The choice of proper eye-protection equipment should be made by a responsible person who fully understands what it should consist of, and he should be guided by the specifications as detailed in the American Standard, *Safety Code for the Protection of the Head, Eyes and Respiratory Organs.*

Lenses suitable for gas welding or cutting should not be depended upon for protection against the rays from arc welding. It should be noted that special precautions must be taken to protect other workers or passersby from the harmful rays given off in arc-welding operations. It is preferable to locate such jobs in special areas. If this is impractical the operation should be screened or enclosed not only to prevent workers or passersby from looking directly at the arc, but also to protect them from reflected rays as much as possible. Further protection against reflected rays is frequently provided by applying non-light-reflecting paint to the screen or enclosure and to other nearby surfaces. Zinc oxide combined with lampblack to produce a blue-gray color is satisfactory.

Goggles suitable for gas welding are satisfactory for thermit welding.

Welders should wear suitable goggles to protect the eyes when removing slag from welds and when chipping and grinding welds.

For helpers and others who must work in the vicinity of heavy arc-welding operations suitably colored goggles are recommended if screen protection or the like is not provided.

Goggle frames preferably should be of a material which is a poor conductor of heat, easy to sterilize, not readily flammable and should have suitably designed vents in the cups to provide ventilation back of the lenses without admitting glare from the work.

Face shields are recommended for operators of resistance-welding machines for the purpose of protecting eyes and face from flying molten metal.

HEALTH—VENTILATION—PROTECTIVE EQUIPMENT

The actual health hazards from welding and cutting operations are relatively few and these can be guarded against by following simple precautions or by using equipment readily available.

Hazards to health may arise from the gases, fumes or dust which may be present during operations because of the materials used and the materials being welded including fluxes and electrode coatings. Harm resulting from contamination of the air can be avoided by proper ventilation. Ventilating equipment is nearly always needed where welding or cutting is done in small, closely confined spaces as in tanks. In the holds of ships very definite steps must be taken to insure proper conditions. Conditions vary so much and depend upon the shop and the job being undertaken to such an extent that it would be very difficult to establish a single standard for ventilation based on rate of air change. In general, it may be said that ventilation must at least insure good visibility and a comfortable working temperature.

Acetylene is a simple anesthetic, not a poison. Concentrations in the order of 40% or more are required to produce anesthesia. Acetylene made from calcium carbide produced on the North American continent contains such slight quantities of any hazardous impurities that they may be disregarded. Furthermore, as the lower explosive limit of acetylene in mixture with air is approximately $2^1/_2$ to 3%, it is obvious that where a flame is employed, an explosion would occur before concentrations of anesthetic proportions could be developed. Acetylene in very high concentrations would suffocate a human being owing to exclusion of sufficient oxygen.

Under ordinary conditions, when the welding of clean carbon steel is carried on in large or well-ventilated areas, experience has shown that no health hazard exists.

Under certain conditions of welding, health hazards due to gases, fumes or dusts may exist. These possible hazards are not serious except when operating in spaces not properly ventilated and are almost entirely due to the presence of gases, dusts and fumes containing lead, zinc, cadmium, fluorine or compounds thereof. When such hazards are present, sufficient ventilation or individual respiratory protection must be provided.

Lead is a hazard during the welding or cutting of material which may have been heavily coated with lead paint, or material containing lead. Lead occurring as an impurity in brass, bronze or zinc would seldom present a hazard. In nearly all cases where welders have contracted lead poisoning, it has been the result of cutting materials heavily coated with lead paint, as may be the case in scrapping of railroad cars, ships or structural iron

work, but as indicated, this can be controlled by using adequate protective measures. Special steels containing lead may present a hazard, in proportion to the amount of steel melted. The Bureau of Mines has approved a special type of filter mask for protection from lead fumes under certain conditions, but air-line masks are recommended as the most positive protection under all conditions.

The fumes of cadmium are occasionally encountered, as in the welding of cadmium-coated material, and may cause serious congestion or edema of the lungs if inhaled in high concentration or for long periods.

Metal fume fever, or generally more commonly called *zinc chills*, may follow exposure to zinc fumes resulting from welding operations on galvanized material, brass or bronze, and at times from the use of bronze filler metal. It should be emphasized that zinc chills, though annoying, do not represent a serious health menace such as lead poisoning. Metal fume fever is an acute, self-limiting condition without known complications, aftereffects or chronic form. An attack usually comes on after a day's work, seldom lasts as much as 24 hours, and does not usually recur on repeated exposure unless there has been an interval of at least several days between exposures. Operations involving evolution of zinc fumes require ventilation for their removal. This often calls for local exhaust ventilation. For occasional exposure, a proper type of filter respirator may give adequate protection.

No known cases of beryllium poisoning resulting from welding or cutting operations have been reported. However, because of the harmful effects reported by other industries it is advisable to take precautions when welding or cutting metals containing beryllium. Until more definite information is available the same protective measures are advised as for lead and cadmium.

Manganese poisoning has been suggested as a possible health hazard. Manganese is present only in alloy with iron in steels on which welding and cutting work is performed. Under such conditions experience indicates that no dangerous amount of manganese fumes is produced. No cases have been reported from such a source but adequate ventilation should be provided.

Fluxes containing fluorides, such as are often used in gas welding and brazing of aluminum or stainless steels, may produce a fume which is very irritating to the respiratory tract. The action is that of a local irritant, but concentrated fumes may lead to severe congestion. Other elements may form irritating fumes. For operations in confined spaces, local exhaust ventilation for the removal of the fumes is essential.

The coatings on stainless steel electrodes contain compounds bearing fluorine, but under ordinary conditions of use, it is doubtful that harmful amounts of fumes are produced.

From time to time there have been unconfirmed statements alleging injuries to welders from carbon monoxide. Naturally, minute quantities may be present in any flame, but so far as the welding industry is concerned, it is quite unlikely that any harmful amount could accumulate if precautions in regard to working in confined spaces are followed. Small amounts may be given off when the flame first impinges on cold metal, but in general it may be said that in ordinary use of the welding or cutting processes the operator is exposed to even less carbon monoxide than a traffic policeman on a busy corner or a housewife in a small kitchen.

Oxides of nitrogen may be formed under some conditions by the action of heat on the nitrogen and oxygen in the air. The action is easily reversible, and the gas formed is very unstable. Under ordinary conditions, no oxides of nitrogen will be found in the air breathed by a welder.

Other fumes may be encountered from time to time, not due to any materials connected with the welding process itself but due to the heating of various residues, sludges, etc., which might be present on the material. These usually are hazardous only in very confined spaces, as in tanks. In such locations, surfaces to be welded should be well cleaned and local exhaust or other ventilation provided to insure removal of the fumes.

With the exception of the lead and cadmium hazard in work on lead and cadmium-coated material and the less serious hazards from zinc fumes, the only important health hazards in welding are

due to operations in small, closely confined spaces: these can be avoided by proper ventilation or individual respiratory protective equipment. Ventilation must be directed at the removal of the fumes and gases, and in confined spaces this means local exhaust or forced-air ventilation, at least sufficient to insure good visibility for the work. Under such conditions there will be few, if any, health hazards.

Oxygen must not be used for ventilation purposes as increased concentrations of oxygen in air cause combustible material such as clothing to burn more rapidly.

More detailed information on ventilation requirements will be found in the American Standard, *Safety in Electric and Gas Welding and Cutting Operations.* (See Chapter 62 for further information on this subject.)

Clothing

Protective clothing required for any welding or cutting operation will vary with the size, nature and location of the work, but in all cases, it should be sufficient to protect the welders from burns from spatter and in the case of arc welding or cutting from the radiant energy from the arc. The following general rule will be helpful.

Woolen clothing is preferable to cotton because it is not readily ignited and because it helps protect the welders from changes in temperature.

Outer clothing such as jumpers and overalls should be free from oil or grease.

As sparks, hot slag or hot metal may lodge in rolled-up sleeves, in pockets or in the cuffs of overalls or trousers, it is highly desirable that sleeves and collars be kept buttoned and that pockets be eliminated from the front of overalls and aprons. Low shoes with unprotected tops should not be used. Safety shoes are recommended.

Capes or shoulder covers made of leather or other suitable material should be worn during overhead welding operations. Skull caps of flame-resistant cloth or leather may be worn under helmets to prevent scalp burns.

For overhead welding and welding in extremely confined spaces, ear protection is sometimes desirable. This may be accomplished by placing wool or rubber plugs in the ears or by covering them with wire screen protectors.

Flame-proof aprons, made of leather, asbestos, or other suitable material, may also be desirable as protection against radiated heat and sparks.

Where there is exposure to sharp or heavy falling objects, hard hats or head protectors should be used.

Except when engaged in very light work, all welders should wear flame-proof gauntlet gloves, preferably of leather.

All clothing and gloves should be kept in good repair. Wet or worn gloves or clothing have lost their protective qualities.

Leather clothing when used should conform with the American Standard, *Specifications for Protective Occupational Clothing, L18.*

BIBLIOGRAPHY

1. *American Standard Safety Code for the Protection of Head, Eyes and Respiratory Organs (Z2)* National Bureau of Standards Handbook H24, 1938.
2. *Procedure to Be Followed in Preparing for Welding or Cutting Certain Types of Containers Which Have Held Combustibles,* American Welding Society, 1940.
3. *Minerals Used in Welding,* Ralston and Von Bernewitz, U.S. Bureau of Mines, June 1940.
4. *Pathology of Shielded Arc Welding,* Von Hoam and Groom, Journal of Industrial Hygiene and Toxicology, February 1941.
5. *Gas Welding and Flame Cutting,* Safe Practice Bulletin No. 23, National Safety Council, 1941.
6. *Health Aspects of Welding,* Drs. A. G. Cranch and B. L. Vosburgh, National Safety Council, 1942.
7. *Health Aspects of Welding,* Drs. A. G. Cranch and B. L. Vosburgh, The Welding Journal, May 1943.
8. *Health Control in Welding,* Dr. Philip Drinker, California & Western Medicine, July 1943.
9. *Machine and Electrode Standards Publication No. 45-105,* National Electrical Manufacturers Association, September 1945.
10. *Safety in Electric and Gas Welding and Cutting Operations, Z49.1,* American Standards Association, 1944.
11. *Shipyard Health Problems,* Dr. Philip Drinker, Journal of Industrial Hygiene and Toxicology, March 1944.
12. *Electric Welding,* Safe Practice Pamphlet No. 105, National Safety Council, May 1944.
13. *Welding Fumes in Steel Fabrication,* P. Drinker and K. W. Nelson, Industrial Medicine, September 1944.
14. *Safe Practices for Installation and Operation of Oxy-Acetylene Welding and Cutting Equipment,* International Acetylene Association, 1947.

15. *National Electrical Code,* National Board of Fire Underwriters, 1947.
16. *Health of Arc Welders in Steel Ship Construction,* Public Health Service Bulletin No. 298, Supt. of Documents, 1947.
17. *Gas Systems for Welding and Cutting,* Pamphlet No. 51, National Board of Fire Underwriters, January 1947.
18. *Regulations Prescribed by the Commandant of the Coast Guard Governing Explosives or Other Dangerous Articles on Vessels,* Revised July 1, 1947, Treasury Dept., U.S. Coast Guard, Washington, D.C.
19. *API Manual on Cleaning Petroleum Storage Tanks,* American Petroleum Institute, July 1948.
20. *Drums, Handling, Cleaning and Filling,* National Safety Council (latest issue).
21. *List of Inspected Gas, Oil and Miscellaneous Appliances,* Underwriters' Labs. (latest issue).

CHAPTER 47

BUILDINGS*

INTRODUCTION

THIS CHAPTER IS intended to cover those structures which are subjected essentially to static loading such as would be encountered in building construction. For those portions of buildings, such as crane girders, or members carrying moving machinery, or for structures such as bridges, where variations in loading intensity occur rather frequently (see Chapter 48, Bridges).

CODES AND SPECIFICATIONS

For the control of welding, in the fabrication and construction of steel frame buildings, the AMERICAN WELDING SOCIETY has adopted and issued the *Standard Code for Arc and Gas Welding in Building Construction.* This Code has been revised periodically so that the current edition, which was issued in 1946, represents present accepted good practice. The most outstanding revision in the 1946 edition was the increase in unit stresses in butt welds so that they are now equal to the corresponding unit stresses in the base metal. It is intended that the Code deal primarily with welding requirements only.

The American Institute of Steel Construction *Specification for the Design, Fabrication and Erection of Structural Steel for Buildings by Arc and Gas Welding* (current edition dated 1946) accepts the provisions of the American Welding Society Code and provides for the design, fabrication and erection of the structure as a whole.

These two documents, referred to throughout this chapter as the Code and the Specification, respectively, provide, for the benefit of building officials, designers and constructors, a complete and authoritative coverage of the recognized best practices in the design and construction of welded steel building frames. In addition to these two fundamental publications many city, town, state and district codes have been promulgated for the control of building construction. Engineers concerned with the construction of steel buildings should be familiar with the Code, the Specification and any local codes or other regulations applicable to the particular structure in the locality where such construction is contemplated.

MATERIALS

Both the Code and the Specification require that steel used for buildings must conform to ASTM *Steel For Bridges and Buildings* (Serial Designation: A7). This steel is of proved weldability and is practically the only grade of steel used for rolled shapes employed in building construction, although details such as base plates, plate stiffeners, rigid frame knees, etc., may be fabricated from *Structural Quality Carbon-Steel Plates* (ASTM Designation: A283). Specifications for other steels suitable for building construction are indicated in Table 1.

Table 1—Additional Steels Suitable for Building Construction

Hot-rolled carbon-steel bars	ASTM A107
Structural steel for ships	ASTM A131
Low-alloy structural steel	ASTM A242 (Welding Quality)
Mild- to medium-strength carbon steel castings for general applications	ASTM A27 (Weldable Grades)
Wrought iron, bars, refined iron	ASTM A41
Wrought iron plates	ASTM A42
Shapes and bars, rolled wrought iron	ASTM A207
Federal specification	QQS 741 Grade A (Bridges), Type II (Welding Quality)

* Prepared by a committee consisting of H. W. Lawson, Consultant, *Chairman;* LaMotte Grover, Air Reduction Sales Co.; T. R. Higgins, American Institute of Steel Construction; C. L. Kreidler, Lehigh Structural Steel Co.; H. M. Priest, U.S. Steel Corp.; R. E. Spaulding, Consultant.

Some of the other materials which have been used in riveted construction to some extent but which are comparatively difficult to weld with any degree of reliability are not covered by the provisions of the Code and Specification. Such materials include structural silicon steel, structural nickel steel or similar medium- and high-tensile steels. The Code provides means for obtaining acceptance for welding those materials which may not be considered as prequalified. Prequalification may not be assigned to old materials such as wrought iron, whose analysis and structure are unknown.

At the present time virtually all welding in building construction is performed manually by the shielded metal-arc welding process. Procedures for this process, or for gas welding, when performed in accordance with the Code and Specification have a prequalified status, while the use of automatic welding employing submerged arc welding or other automatic equipment requires that the joint welding procedures be qualified before such welds may be deemed acceptable.

Some research has been undertaken on the effect of resistance welding through mill scale and rust, and further research is now in progress which eventually will result in establishing values for resistance welds in structural thicknesses of materials.

The electrodes that are used for this class of structure are almost exclusively of the E60 series. For shop welding of deep groove welds E6030 may sometimes be used, although most shop work on positioned welds is performed with E6020 electrodes. Tack welds and welds which are not readily positioned are usually made with E6010 electrodes.

For field welding, deep groove welds are occasionally welded with E6020 electrodes. Generally, for quality work with good fit-up, E6010 electrodes are most suitable, while for poor fit-up, such as is quite common to simple beam and column structures, the use of E6012 electrodes is preferred.

Each structure must be studied carefully when determining the type or types of electrode to be used in the field in order to reduce to a minimum the variety of electrodes employed. Generally, changes in polarity and in current settings are not too easily accomplished and delay and error may be the result of too great a variety of types and sizes of electrodes. This is not as applicable to shop work where the factors involved in the positioning of the work, and in the selection of electrode types and sizes, may be more efficiently balanced to produce higher quality at lower cost. A more complete description of the electrodes available and their qualities and applications is presented in Chapter 38—Filler Metal.

Where special materials or special electrodes are required in connection with new or repair work, it is recommended that a specialist be consulted; either a Consulting Engineer, specializing in this type of problem, or a manufacturer's service department experienced on the special materials or the particular adaptation.

DESIGN

General

The busy practical designer, following standardized specifications and rules for designing and detailing riveted structures, is inclined to think of steel material as coming from the mill in a stress-free condition; proceeding through all the operations of shearing, punching, bending, assembling, riveting, handling, shipping and erection without undergoing any permanent deformation or plastic flow of the material, and without being subjected to any stresses or strains beyond the elastic limit of the material. It is assumed that the material, once it is connected in place in a structure, is entirely free from all stresses except those due to load, and that the loads are concentrated or distributed uniformly in an ideal pattern and are of the amounts assumed. Further, that if ever, at any point, an excess loading should produce a local stress exceeding the yield point, failure would instantly and inevitably result.

On the contrary, regardless of the materials and methods of construction employed, the materials are invariably subjected to plastic deformations during the various operations of fabrication and erection, as well as while they are becoming adjusted to service loads in the structure. Also, some parts of the structure are certain to possess high internal stresses, often of yield point intensity, such as those resulting from shrinkage

after rolling, in the case of structural steel. Not only is this true of structural steel, it is well recognized that high internal stresses and plastic flow are involved in concrete and timber structures as well, although steel is generally better adapted to such behavior. Riveted truss bridges, with calculated secondary stresses much greater than the primary design stresses, have given satisfactory service for years. Many of the joints of riveted tier buildings and the component parts of trusses and girders, exhibit evidence of plastic flow both before and after they have been in service.

The internal stresses involved, whether temporary or residual, are usually balanced and of a self limiting nature, hence, there is nothing to cause resulting deformations to progress to failure. Research and experience indicate that high peaks of internal stress become ironed out through local plastic flow upon applications of external loading provided the material has a reasonable amount of toughness and ductility, and the details of design and construction operations do not produce excessive stress concentrations or make unreasonable demands upon the ability of the material to deform plastically, and do not seriously constrain plastic deformation. It should be apparent from this discussion and from the results of recent research, that a great many of the doubts connected with the residual stresses known to be created by welding operations are unfounded.

When a weld is undergoing the severe shrinkage incidental to rapid cooling, internal stresses are inevitable. Cracking may occur in welds where the metallurgy or the geometrical proportions in and around the joints are very unfavorable to plastic behavior. This has caused considerable concern to structural designers unfamiliar with the factors involved; causing doubt as to the adequacy of those structures where *residual stresses* may have been produced by welding. They have believed that, due to the heating and cooling incident to welding, residual stresses exist in various parts of the structure, or its connections, in amounts just short of those necessary to produce failure, and that failure will result in such areas upon the application of even a small part of the design load. However, this is not true. If conditions are normal, so that the weld cools to room temperature without cracking, it is unlikely that the residual stresses developed during the cooling will have any appreciable effect upon subsequent behavior of the joint. A more extended discussion of residual stresses is presented in Chapter 43, Thermal and Mechanical Treatment of Welded Assemblies, covering shrinkage, and the importance, control and relief of residual stresses. An understanding of these phenomena is desirable to adequately visualize the behavior of a complicated welded frame.

Design of Frames

It is necessary also to make certain assumptions as to the behavior of the joints and to so design the joints that their actual behavior conforms to the design assumptions. Thus, if a frame is proportioned to support the loads as a rigid frame in which the distribution of stress is predicated upon the elastic behavior of the frame, the joints must function without sensible angular distortion, or if designed as a simple frame, the joints must not produce more restraint than can be carried safely by the welds which connect them.

Tests of various beam-to-column connections have been conducted for the Welding Research Council at Lehigh University to determine the suitability of certain types of connections for rigid, semi-rigid and simple beam framing. Moment-rotation curves may be plotted, as shown in Fig. 1. On this diagram a so-called *Beam Line* may be plotted. The beam line may be drawn for any design conditions of load distribution and l/d ratio of beam; the equation of the line being

$$M = M_f - \frac{2EI\phi}{l}$$

where

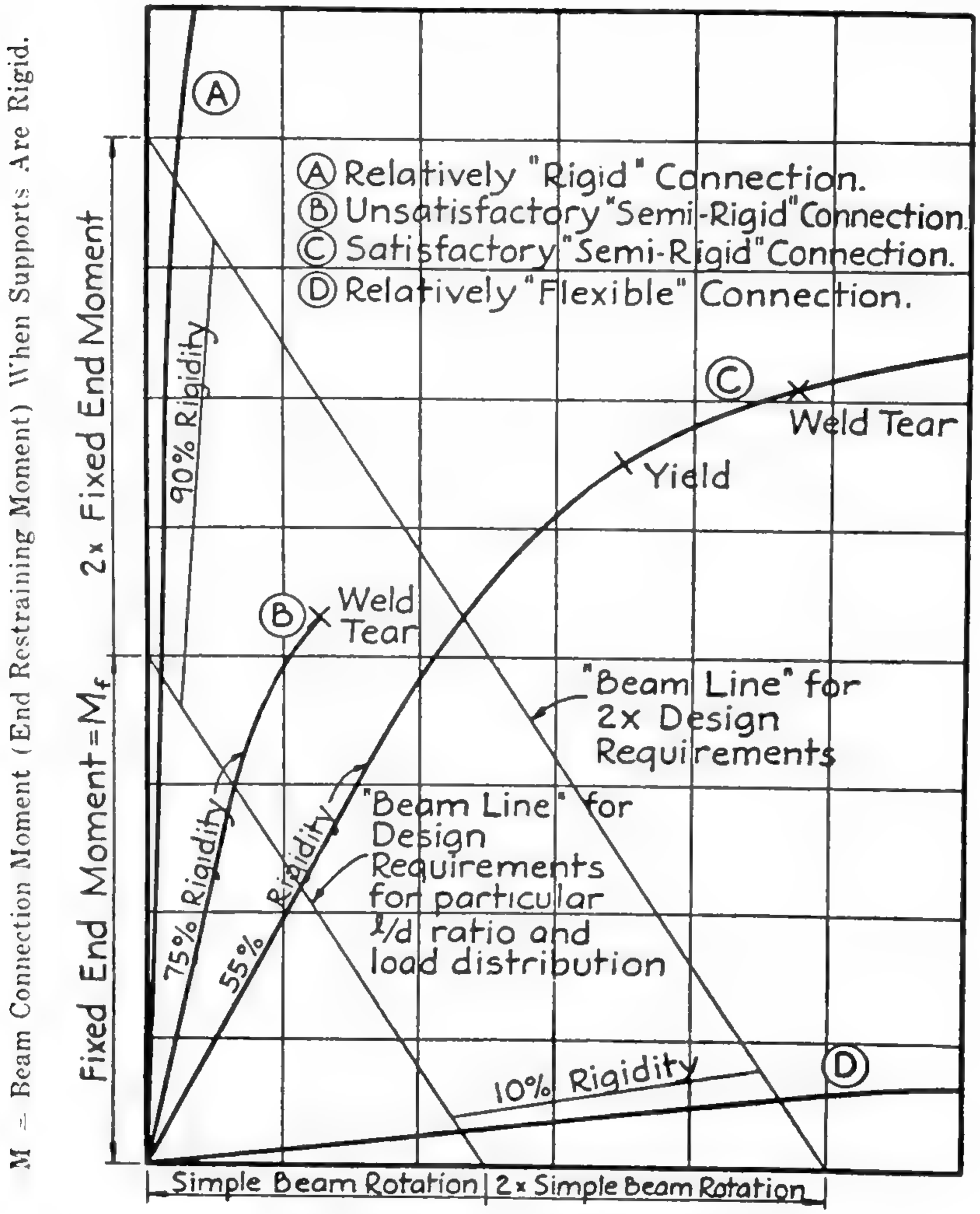
M = End restraining moment
M_f = Fixed-end moment
E = Modulus of elasticity
I = Moment of inertia of section
ϕ = Deflection angle in radians
l = Length of span

(See any American text on the slope-deflection method of beam analysis.) The intercepts on the M axis and the ϕ axis, as shown on the diagram, may be readily

computed for a particular beam span and load and the beam line drawn joining the intercepts.

The addition of a second beam line, at 2 times or 1.67 times the design requirements, aids in the determination of the relative suitability of those connections exhibiting excessive rotation or weld failure beyond the limits of the beam line.

If the design is predicated upon the assumption of simple beam framing, the connections should be such that as little resistance to rotation is offered as it is practicable to obtain. Conversely a rigid detail should permit no sensible rotation. Since this degree of rigidity is difficult to obtain, and slightly less restraint results in lower maximum beam moments there would appear to be some advantage in designing for partial restraint. (See Fig. 2.)



θ = Slope at End of Beam = ϕ, the Connection Rotation Between End of Beam and Rigid Support.

Fig. 1.—Moment and Rotation Design Requirements for Beam-to-Column Connections

Types of Construction

These three general types of framing are defined by the Specification as follows (see Fig. 3):

"*Type 1,* hereinafter designated as *rigid frame* (continuous restrained frame), assumes that the end connections of beams or girders and all other members in the frame have sufficient rigidity to hold virtually unchanged the original angles between such members and the members to which they connect.

"*Type 2,* hereinafter designated as *conventional* or *simple* framing (unrestrained, free-ended), assumes that the ends of beams and girders are connected for shear only, and are free to rotate under load.

Type 3, hereinafter designated as *semi-rigid framing* (partially restrained), assumes that the connections of beams and girders possess a dependable and known moment capacity intermediate between the complete rigidity of Type 1 and the complete flexibility of Type 2.

"All welded connections shall be consistent in their design with the assumptions as to types of constructions, as called for in the design drawings."

The Specification provides for wind bracing in Type 2 construction (conventional, simple) to be designed under either of two assumptions: that the wind connections are adequate to resist the moments induced by the gravity loading and the wind loading at the increased unit stresses provided therefor, or that the wind connections, designed to resist the assumed wind moments, are so designed that larger moments induced by the gravity loading under the actual conditions of restraint will be relieved by deformation of the connection material without overstress in the welds.

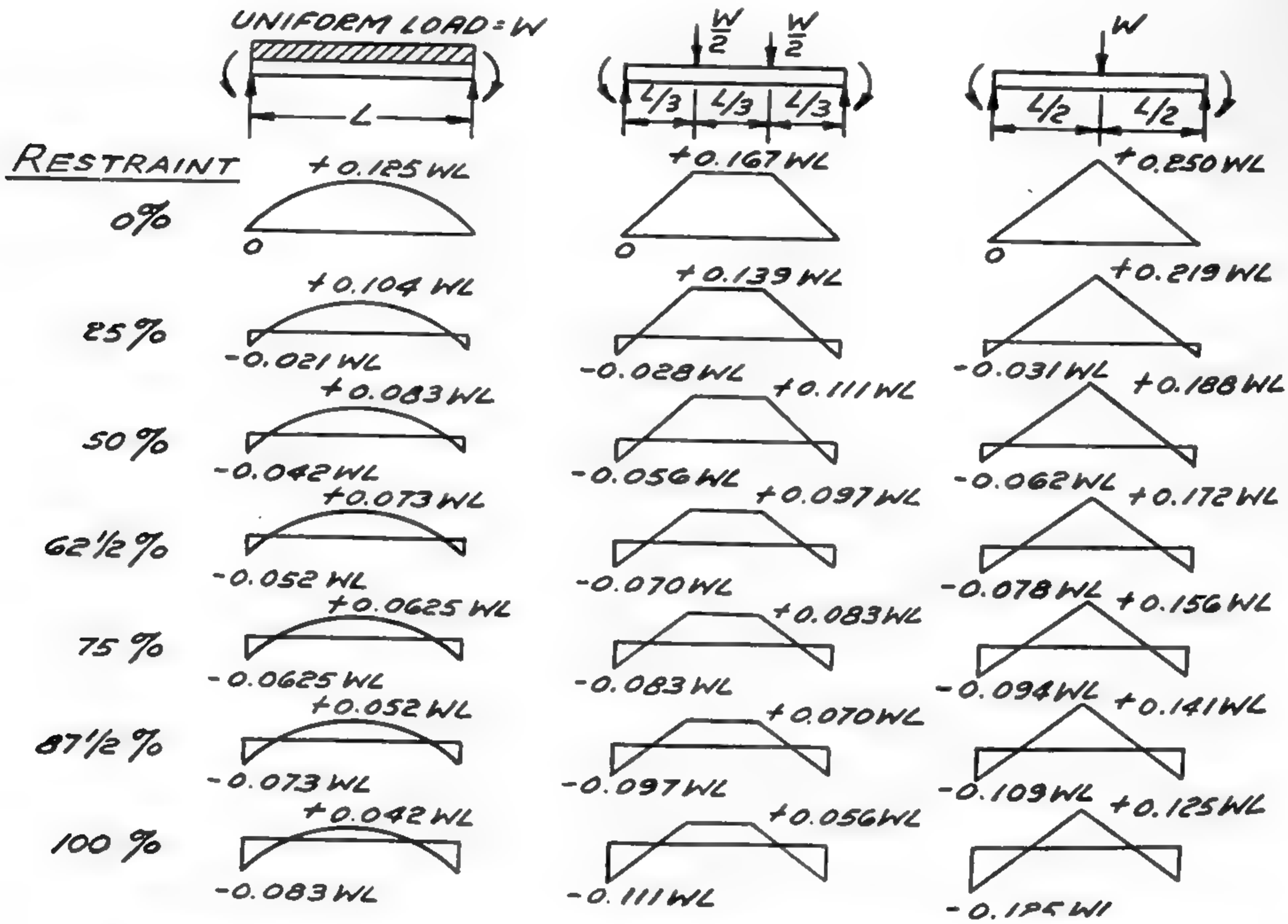


Fig. 2.—Effects of Various Degrees of End-Restraint Upon Bending Moments of Beams

The Specification further states that Types 2 and 3 construction may necessitate some non-elastic but self-limiting deformation of a structural steel part, but under forces which do not overstress the welds.

Since it is necessary for the details of welded structures to produce the degree of restraint assumed in the design of the structure, the designer must indicate definitely in the specifications and on the

drawings, the design assumption with respect to type of construction as described above. He should also show on the drawings the principal moments and shears.

While no definite values have been set up in the Specification for the relative rigidities applicable to the three types of construction, it may be assumed that

nections which accomplish a similar result by plastic flow in the connection material.

By percentage of rigidity is meant the ratio of the moment developed by the connection, with no column rotation, to the moment developed by a fully rigid connection under the same conditions, multiplied by one hundred.

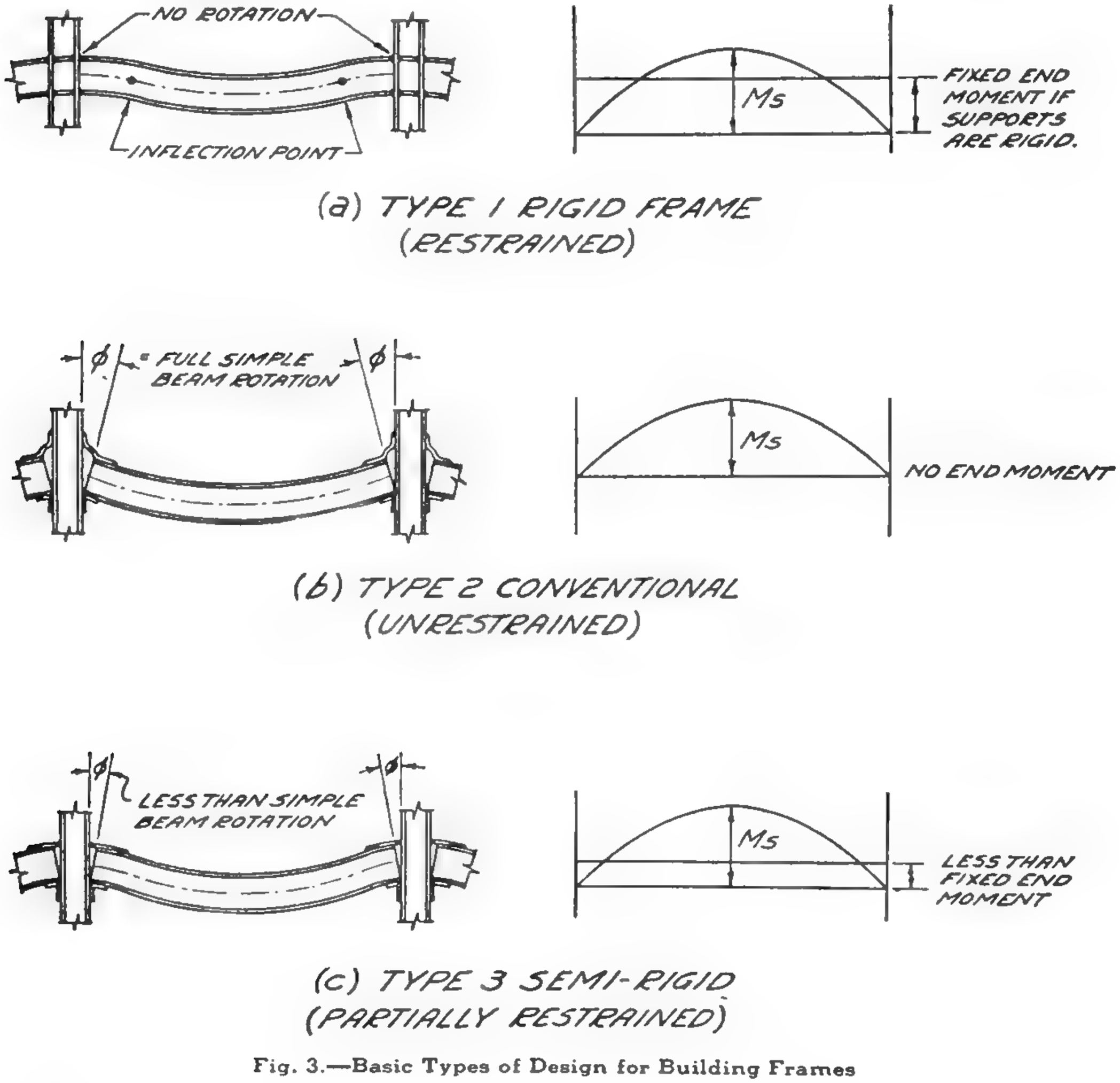


Fig. 3.—Basic Types of Design for Building Frames

joints for Type 1 (rigid) construction must provide not less than 90% rigidity, and for Type 3 (semi-rigid) construction approximately the degree of rigidity assumed in the design of the structure. For Type 2 (simple) construction the joints must provide a degree of restraint low enough to avoid overstress in the connection welds, or other structural damage. This can be accomplished either by the use of flexible connections, or con-

Tests have been made on a number of types of details making possible the establishment of percentages of rigidity for these types, No attempt has been made to officially establish such values, but, it is contemplated that the American Institute of Steel Construction will publish established values of relative rigidities from time to time. Such information is available today, only in the form of reports of research to the AISC and

to the Welding Research Council of the Engineering Foundation. The research covered by these reports has been conducted at Lehigh University by Inge Lyse, Bruce Johnston, Cyril Jensen, R. M. Mains and Associates, and is listed in the bibliography at the end of this chapter.

Since welds are inherently quite rigid, the resulting continuity of welded assemblies makes this joining method particularly applicable to rigid frames. There is also a decided advantage in compactness of joint with attendant savings in connection material, and a simplicity of joint which enhances the appearance of the finished structure where the steel work is left exposed. It is therefore in the rigid frame that welding has been employed most effectively in building construction. This is particularly true of frames one or two panels high such as are employed in industrial buildings. While theoretically there should be substantial savings in multi-story structures, the frame analysis involves so great an amount of labor, even with the short cuts possible by methods employing moment distribution, that tier buildings are usually designed as Type 2 (simple) structures using some empirical method of wind stress determination.

For simple beam connections, seats with or without stiffeners are usually combined with flexible top angles. Where such connections must also resist lateral forces a flat plate is used for the top connection, butt welded to the column flange and fillet welded to the top flange of the beam. The plate is designed to resist a wind moment at the usual unit stress permitted for members subjected mainly to wind load stresses, under the assumption that should this stress be increased by the addition of gravity loads beyond the yield point of the plate, plastic flow in the connection plate will occur. The horizontal element of the beam seat must also be designed in a similar manner, giving consideration to the possibility of reversal of lateral forces. The actual design of this type of joint is discussed under Design of Joints.

No extended discussion of Type 3 (semi-rigid) construction is possible in the limited space available in this HANDBOOK. An examination of the diagram of Fig. 2 will readily show that for uniform loading or concentrated loads disposed to approximate uniform loading, that the lowest maximum stress in the beam occurs when the joint produces 75% restraint. Tests of welded top plate connections designed for full restraint indicate that a restraint of 85 to 95% may be expected, since local deformations of column flange and connection material are such that it is practically impossible to attain 100% rigidity. If then the joint is assumed to be say 87½% restrained, a saving of about 15% in maximum moment results. Any reduction in actual restraint down to 62½% (that is 25% less than expected) would result in a decrease in beam end moment and an increase in center moment without any increase in the design moment. An increase in restraint caused by producing a stiffer connection than contemplated would result in an increase in stress in the beam which could not exceed 10%. Overstress of any considerable magnitude in the end connection would be relieved by plastic flow and equilibrium would result, in the range contemplated by the design.

When it becomes necessary to add wind bracing to a Type 2 structure, the transition to Type 3 would seem to represent a decided saving, since the increase in connection material is negligible while the saving in beam weight is appreciable. However, any necessary increase in column material must be taken into consideration, as well as the extra cost of design.

Design of Connections

General.—Research to determine the behavior of welded details has yielded much information of general significance. Whether welded or otherwise connected, the avoidance of severe notch effects, abrupt discontinuities or changes in section, and other forms of severe geometrical constraint, is very significant in the design of dynamically loaded structures such as bridges, crane girders, crane runways, etc., especially if the structures are to be subjected to relatively low temperatures. While there is less need for concern in the case of structural members of the proportions common to building frames under static loading, it is nevertheless advisable to avoid notch-like details and sudden changes in section in so far as practicable, particularly at points where material may be called upon to

yield plastically during construction, or while the structure is becoming adjusted to service under load.

A notch, a sharp re-entrant corner, or any abrupt discontinuity that would interrupt the transmission of stress along smooth lines, will cause a high local concentration of multi-directional stresses, even though the applied loading is uniaxial. From another viewpoint, reflecting what is perhaps the more significant feature of the behavior, the notch causes

NOTE: Concentrations of stress, depicted by short arrows in sketch (*g*), are stresses due to external load, as affected by geometrical shape. They are *not* residual welding stresses.

Fig. 4.—Notch Effects and Stress Concentrations

deformation to be concentrated within such a small volume of metal that the capacity of the metal to deform without fracture is reached prematurely at that point.

The effects of notches and some of the other various forms of stress raisers are illustrated in Fig. 4. In sketch (*a*) a smooth round bar is shown as necking down under tension, and elongating in a ductile manner, before failure. In sketch (*b*) the introduction of a notch is shown resulting in brittle failure of a similar specimen, with no appreciable elongation. The manner in which multi-directional stresses or deformations are set up in the root of the notch is depicted in sketch (*c*).

In sketch (*d*) the presence of a smooth, round hole is shown as causing stress concentrations in the metal adjacent to the hole of about three times the average stress in the net section. If the hole is rough, or the metal ruptured, with the presence of tiny tears, the highly localized stress concentrations may be much greater. Abrupt changes in section produce similar stress concentrations as indicated in sketch (*e*).

Multi-directional stresses at notch-effects and discontinuities act in a manner somewhat similar to multi-directional stresses resulting from external load, depicted in sketch (*f*), because they are unlike other secondary, internal stresses, in that the condition which produces them remains after plastic deformation has taken place, and they are not ironed out and relieved to the same extent as other internal stresses, such as residual welding stresses, are relieved. The effect of these multi-directional stresses is to restrain ductile behavior and raise the yield point so that little plastic deformation can occur to redistribute stresses.

Notch effects produced by incomplete penetration butt welds are illustrated in sketch (*g*), partial length cover plates in sketch (*h*), and similar effects produced by attachments such as lateral connection plates, masonry plates, etc., in sketch (*j*).

Contours which have sharp re-entrant corners, as shown in sketch (*k*), are to be particularly avoided and where such effects occur in highly stressed regions of eccentrically loaded members failure may result at surprisingly low apparent stress as determined by conventional design methods.

Although the effects just discussed are of vital importance to members subject to fatigue, it should be kept in mind that severe notch effects also influence the behavior of steel under static loading, because of their multi-directional effect, and particularly because of their interference with the stress readjustments resulting from plastic flow, which is so important a function in a ductile material. A similar condition may be produced by multi-directional rigidity due to geometrical shape or arrangement of welds. Very thick material in itself constitutes a considerable degree of such constraint.

The combination of notch effects and restraints, accompanied by lower temperatures in the range where tensile strength and ductility are reduced, is not likely to occur in building construction since seldom are such structures called upon to resist such severe loading conditions under reduced temperatures.

In the design of welds and welded details only the amount of welding needed to meet design requirements should be used. Excessive welding may introduce excessive distortion and greater constraint and may greatly increase the cost of fabrication out of all proportion to the respective volumes of added weld metal.

Design of Welds.—The formulas stated in this Chapter have been developed by conventional methods of calculation as presented in elementary texts on strength of materials and have been presented previously in textbooks or articles on the design of welded structures by various authors. In the diagrams and formulas the following notations are used:

V = Vertical reaction or resultant force in lb.
R = Total vertical reaction at the end of a beam in lb.
H = Horizontal reaction or resultant force in lb.
P = Total allowable load to be carried by a connection or group of welds acting together in lb.
e = Eccentricity, in inches, of a load or reaction about the center of gravity of the weld group.
a = (K, B, A, k), a linear dimension in inches (also, in some cases, a ratio).
D = Size of weld in inches (leg size in case of fillet welds). (D

is used also as the depth of a member, in inches).

S = Unit stress in psi.

T or

t = Thickness in inches.

W = One of the dimensions, in inches, of a weld group or of a piece of connection material.

L = Effective length of weld or weld group, in inches.

f_s = Unit shearing stress in psi. upon the throat area of a butt weld, but upon the leg area, $L \times D$, in the case of a fillet weld.

f_m = Unit stress in psi. due to torsion or moment, on the throat of a butt weld, but upon the leg area in the case of a fillet weld.

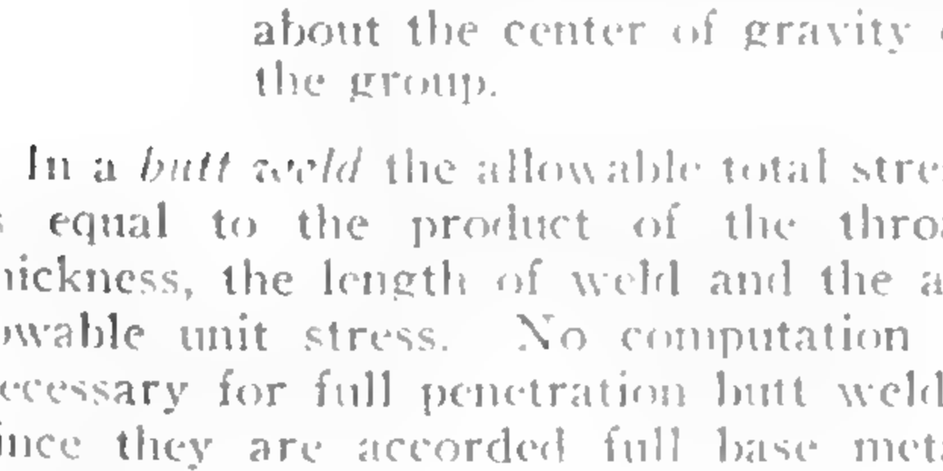
f = Combined unit stress in psi. due to shear and due to torsion or moment, upon the throat of a butt weld but upon the leg area in the case of a fillet weld.

I_p = Polar moment of inertia, in inch units, of a line or group of lines of narrow width, about the center of gravity of the group.

In a *butt weld* the allowable total stress is equal to the product of the throat thickness, the length of weld and the allowable unit stress. No computation is necessary for full penetration butt welds, since they are accorded full base metal values.

In a *fillet weld* the allowable total stress is equal to the product of the weld size (D), expressed in units of one-sixteenth of an inch, as $D/{}^1/_{16}$; the allowable stress per linear inch per one-sixteenth inch size (600 lb.), and the net length of weld in inches (L):

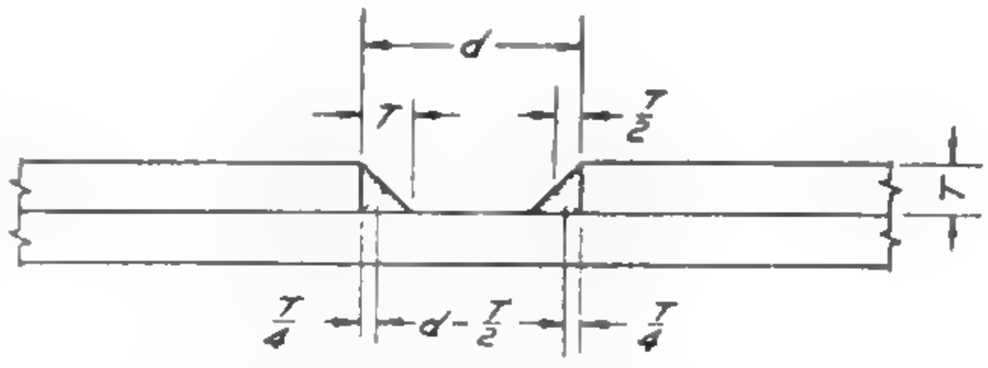
$$P = \left(\frac{D}{{}^1/_{16}}\right) \times 600 \times L$$



This is practically equivalent to a unit stress of 13,600 psi. on the section of the weld throat specified in the Code and Specification ($0.707 \times {}^1/_{16} \times 13{,}600 =$ 601 b. per lin. in. per ${}^1/_{16}$ in. weld size). Fillet welds are considered to be stressed in shear on the throat section for any direction of application of load. While the above formula is convenient for memorizing, the more usual form it is given is $P = 9600\ DL$, or $P = 9.6\ DL$, when P is expressed in kips. A table of allowable loads on fillet welds of various sizes and lengths is shown in Fig. 5.

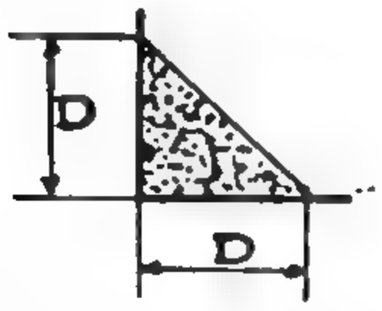
The length of fillet weld in a slot or hole is the average length of the throat of the fillet weld. For a round hole this length is

$$L = \pi\ (d - T/2).$$



The length of a fillet weld is the effective length as described in the Code and Specification. No allowance need be made by the designer for the difference between this net effective length and the actual gross length. The welding operator is required by the Code and Specification to start and stop the welds outside of the desired limits a sufficient distance to produce the required length of full section weld. Where, due to the geometry of the joint, this cannot be done, he will produce a full section weld for the indicated length by running the weld onto an adjoining surface, turning the corner, filling the crater, or by some similar device which will assure a full section weld and avoid craters or reduced weld sections at points of high stress concentration.

Since the allowable unit stress for fillet welds, as provided in the Code and Specification, was determined from tests of joints employing fillet welds rather than tests of weld metal alone, no increase in stress need be considered necessary to provide for the slight eccentricities introduced by the geometry of the fillet weld. However, it is considered good practice in welded design to take into account any other appreciable eccentricities whether or not similar eccentricities would be ignored in a conventional riveted design.



$$P = 9.6DL$$

(Based on 13,600 p.s.i. shear on throat = 9.6 K/d"on leg)

D=Weld Size in inches
L=Weld Length in inches
P=Allowable load in Kips

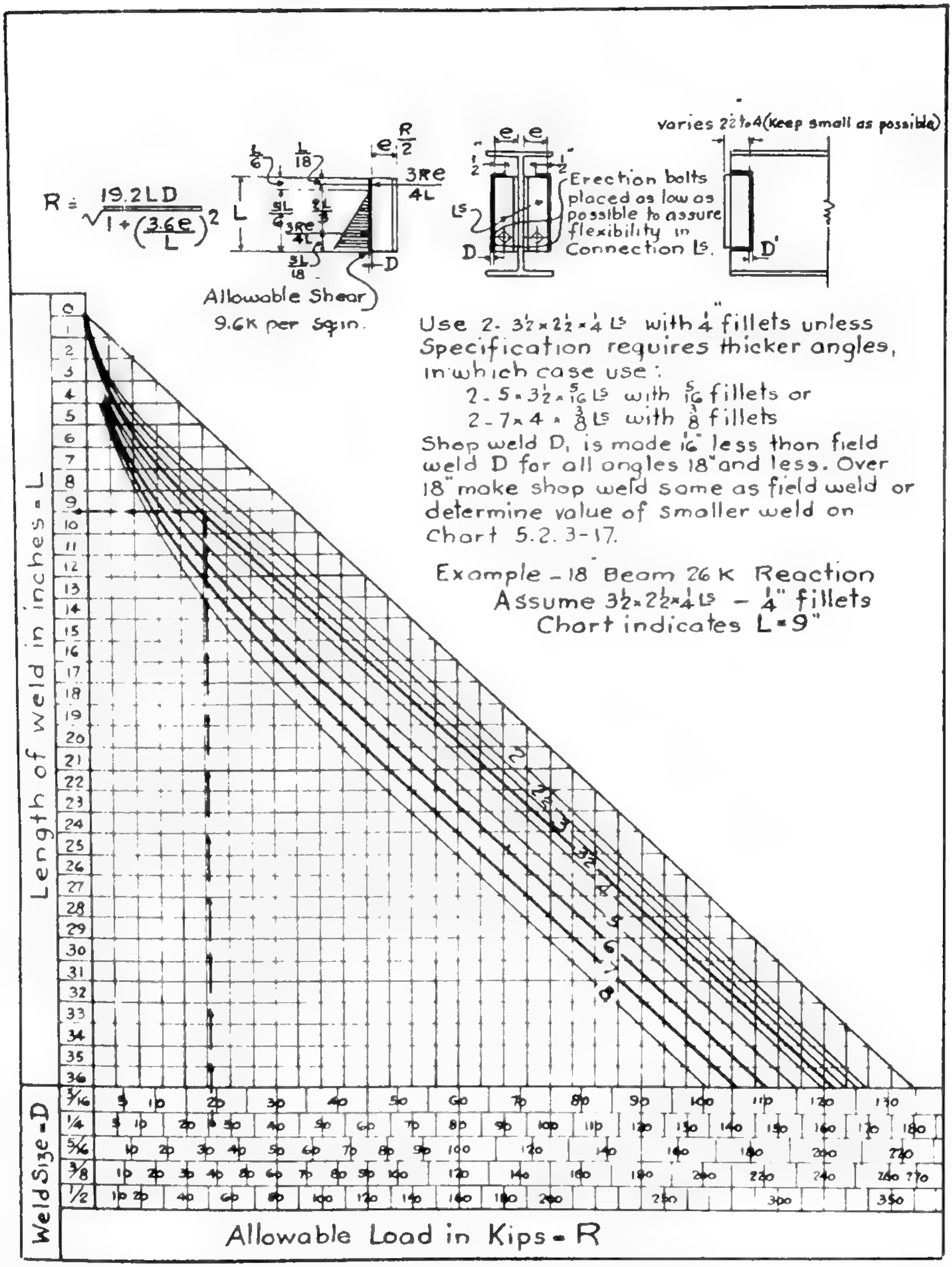
L \ D	1/8	3/16	1/4	5/16	3/8	7/16	1/2	5/8	3/4	7/8	1
.5	.6	.9	1.2	1.5	1.8	2.1	2.4	3.	3.6	4.2	4.8
1.0	1.2	1.8	2.4	3.0	3.6	4.2	4.8	6.	7.2	8.4	9.6
1.5	1.8	2.7	3.6	4.5	5.4	6.3	7.2	9.	10.8	12.6	14.4
2.0	2.4	3.6	4.8	6.0	7.2	8.4	9.6	12.	14.4	16.8	19.2
2.5	3.0	4.5	6.0	7.5	9.0	10.5	12.0	15.	18.0	21.0	24.0
3.0	3.6	5.4	7.2	9.0	10.8	12.6	14.4	18.	21.6	25.2	28.8
3.5	4.2	6.3	8.4	10.5	12.6	14.7	16.8	21.	25.2	29.4	33.6
4.0	4.8	7.2	9.6	12.0	14.4	16.8	19.2	24.	28.8	33.6	38.4
4.5	5.4	8.1	10.8	13.5	16.2	18.9	21.6	27.	32.4	37.8	43.2
5.0	6.0	9.0	12.0	15.0	18.0	21.0	24.0	30.	36.0	42.0	48.0
5.5	6.6	9.9	13.2	16.5	19.8	23.1	26.4	33.	39.6	46.2	52.8
6.0	7.2	10.8	14.4	18.0	21.6	25.2	28.8	36.	43.2	50.4	57.6
6.5	7.8	11.7	15.6	19.5	23.4	27.3	31.2	39.	46.8	54.6	62.4
7.0	8.4	12.6	16.8	21.0	25.2	29.4	33.6	42.	50.4	58.8	67.2
7.5	9.0	13.5	18.0	22.5	27.0	31.5	36.0	45.	54.0	63.0	72.0
8.0	9.6	14.4	19.2	24.0	28.8	33.6	38.4	48.	57.6	67.2	76.8
8.5	10.2	15.3	20.4	25.5	30.6	35.7	40.8	51.	61.2	71.4	81.6
9.0	10.8	16.2	21.6	27.0	32.4	37.8	43.2	54.	64.8	75.6	86.4
9.5	11.4	17.1	22.8	28.5	34.2	39.9	45.6	57.	68.4	79.8	91.2
10.0	12.0	18.0	24.0	30.0	36.0	42.0	48.0	60.	72.0	84.0	96.0
10.5	12.6	18.9	25.2	31.5	37.8	44.1	50.4	63.	75.6	88.2	100.8
11.0	13.2	19.8	26.4	33.0	39.6	46.2	52.8	66.	79.2	92.4	105.6
11.5	13.8	20.7	27.6	34.5	41.4	48.3	55.2	69.	82.8	96.6	110.4
12.	14.4	21.6	28.8	36.	43.2	50.4	57.6	72.	86.4	100.8	115.2
13.	15.6	23.4	31.2	39.	46.8	54.6	62.4	78.	93.6	109.2	124.8
14.	16.8	25.2	33.6	42.	50.4	58.8	67.2	84.	100.8	117.6	134.4
15.	18.0	27.0	36.0	45.	54.0	63.0	72.0	90.	108.0	126.0	144.0
16.	19.2	28.8	38.4	48.	57.6	67.2	76.8	96.	115.2	134.4	153.6
17.	20.4	30.6	40.8	51.	61.2	71.4	81.6	102.	122.4	142.8	163.2
18.	21.6	32.4	43.2	54.	64.8	75.6	86.4	108.	129.6	151.2	172.8
19.	22.8	34.2	45.6	57.	68.4	79.8	91.2	114.	136.8	159.6	182.4
20.	24.0	36.0	48.0	60.	72.0	84.0	96.	120.	144.0	168.0	192.0
21.	25.2	37.8	50.4	63.	75.6	88.2	100.8	126.	151.2	176.4	201.6
22.	26.4	39.6	52.8	66.	79.2	92.4	105.6	132.	158.4	184.8	211.2
23.	27.6	41.4	55.2	69.	82.8	96.6	110.4	138.	165.6	193.2	220.8
24.	28.8	43.2	57.6	72.	86.4	100.8	115.2	144.	172.8	201.6	230.4
25.	30.0	45.0	60.0	75.	90.0	105.0	120.0	150.	180.0	210.0	240.0
26.	31.2	46.8	62.4	78.	93.6	109.2	124.8	156.	187.2	218.4	249.6
27.	32.4	48.6	64.8	81.	97.2	113.4	129.6	162.	194.4	226.8	259.2
28.	33.6	50.4	67.2	84.	100.8	117.6	134.4	168.	201.6	235.2	268.8
29.	34.8	52.2	69.6	87.	104.4	121.8	139.2	174.	208.8	243.6	278.4
30.	36.0	54.0	72.0	90.	108.0	126.0	144.0	180.	216.0	252.0	288.0

Fig. 5.—Allowable Loads on Fillet Welds

For some of the more common cases of eccentricity, the formulas are stated on the design charts in Tables 2 to 9, together with indications of the design assumptions as to stress distribution. A more complete set of charts will be found in the *Manual of Design for Arc Welded Steel Structures,* (see Bibliography), from which much of the design data in this chapter has been taken.

While some of the formulas may not be readily recognizable to structural engineers, this is because of the introduction of the use of proportions in place of finite

Table 2—Allowable Loads on Framed Connections



Weld sizes given at bottom of diagram are for field welds (size = D). For shop weld size, D', see note on diagram or use diagram in Table 3 to determine size required for strength. Also check all weld sizes together with thickness of beam web and thickness of material in supporting member, for compliance with requirements for minimum weld sizes given in Code and Specification.

Framing angles for deep beams should be placed near enough to the top flange to prevent end twisting of beam.

Longer legs of angles are always placed outstanding and are connected to the supporting member

Table 3—Allowable Eccentric Loads on Groups of Fillet Welds

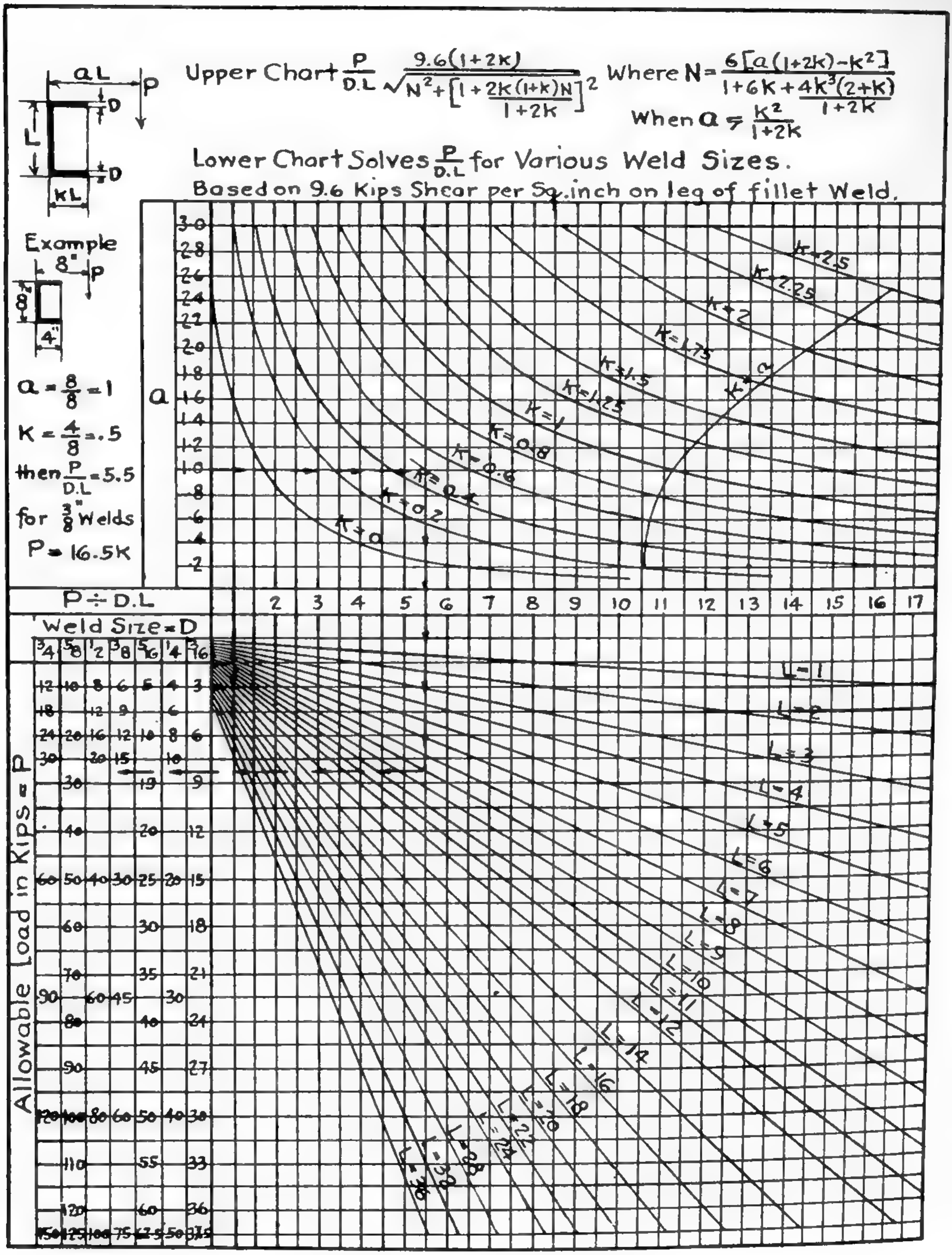


Table 4—Web Crippling of Beams on Seats

R = Reaction or Load

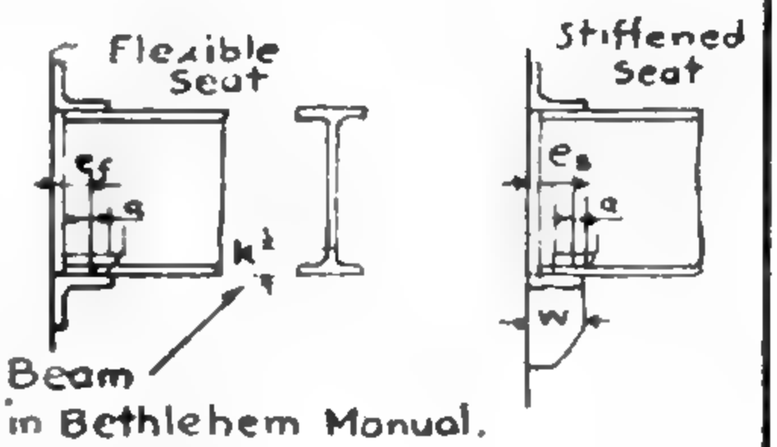
a = Length of bearing on seat to produce 24.000# crippling stress in beam web.

$e_f = \frac{a}{2} + \frac{1}{2}$" for flexible seats See 5.2.3-9

$e_s = w - \frac{a}{2}$ for stiffened seats See 5.2.3-10

From A.I.S.C. Spec.

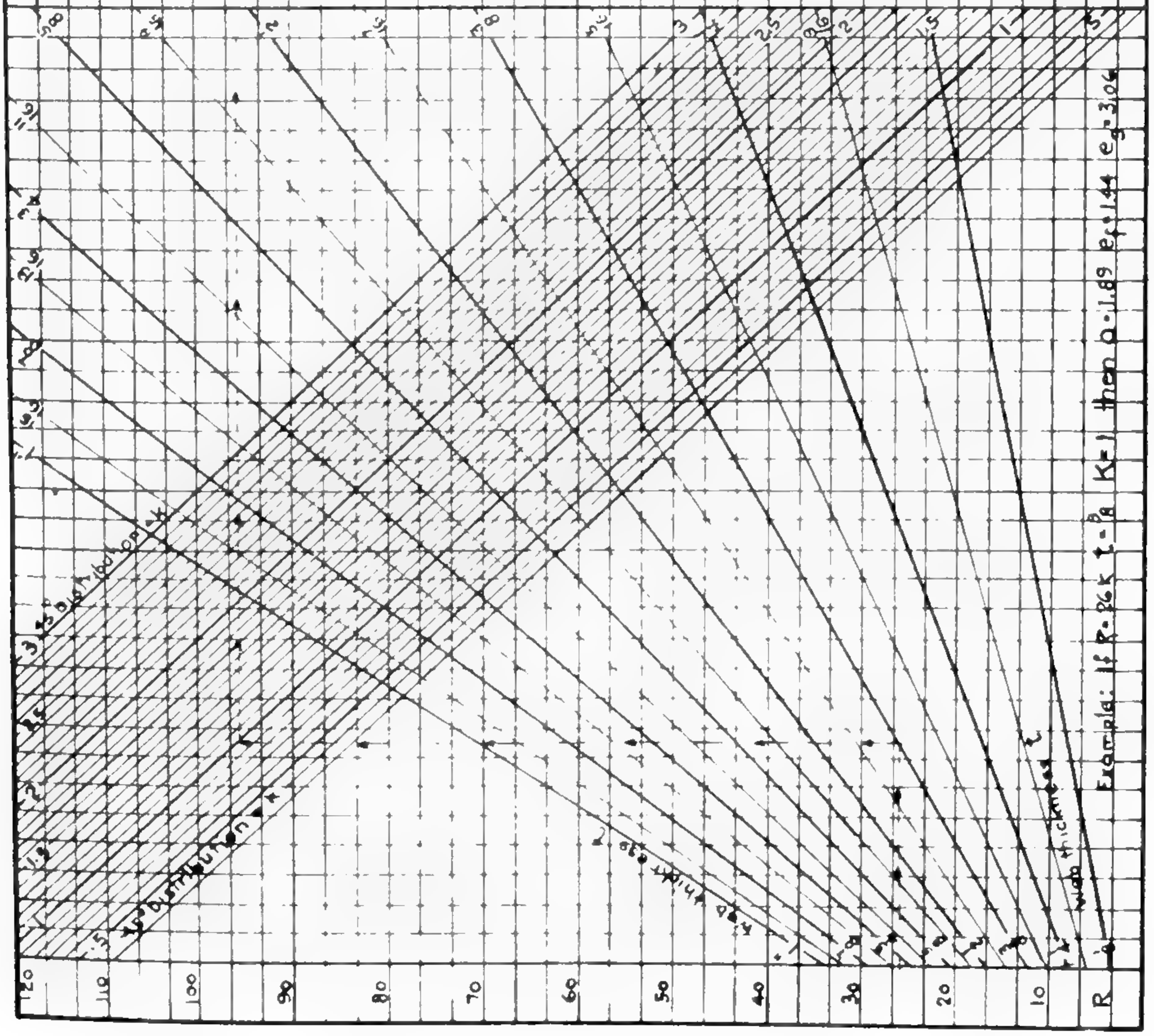
$$Q = \frac{R}{24t} - k$$



Distance from bottom of Beam to edge of fillet = K or O in Bethlehem Manual.

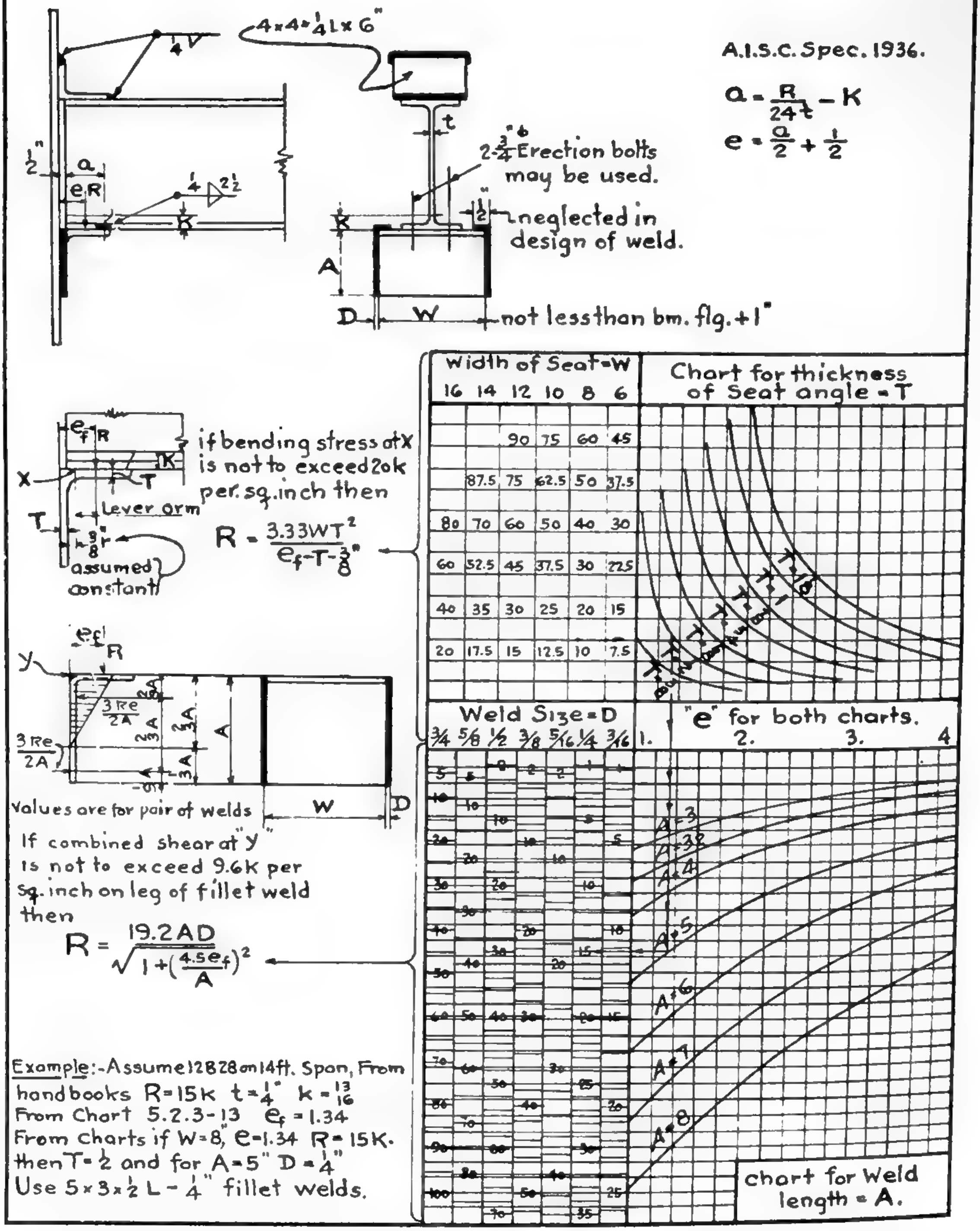
Note e_s may not be less than $\frac{w}{2}$

	w = 4"										w = 5"					w = 6"					w = 7"					w = 8"				
e_s		3.5	3.4	3.3	3.2	3.1	3.0	2.9	2.8	2.7	2.6	2.5	2.4	2.3	2.2	3.1	3.0	2.9	2.8	2.7	3.6	3.5	3.4	3.3	3.2	4.1	4.0	3.9	3.8	3.7	4.6	4.5			e_s
e_f		1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0			e_f
a		1.0					2.0					3.0					4.0					5.0					6.0					7.0			a



In recent edition of AISC Specification N is used instead of a to designate the length of bearing, in inches, and R is used to designate the end reaction, in pounds, rather than in kips.

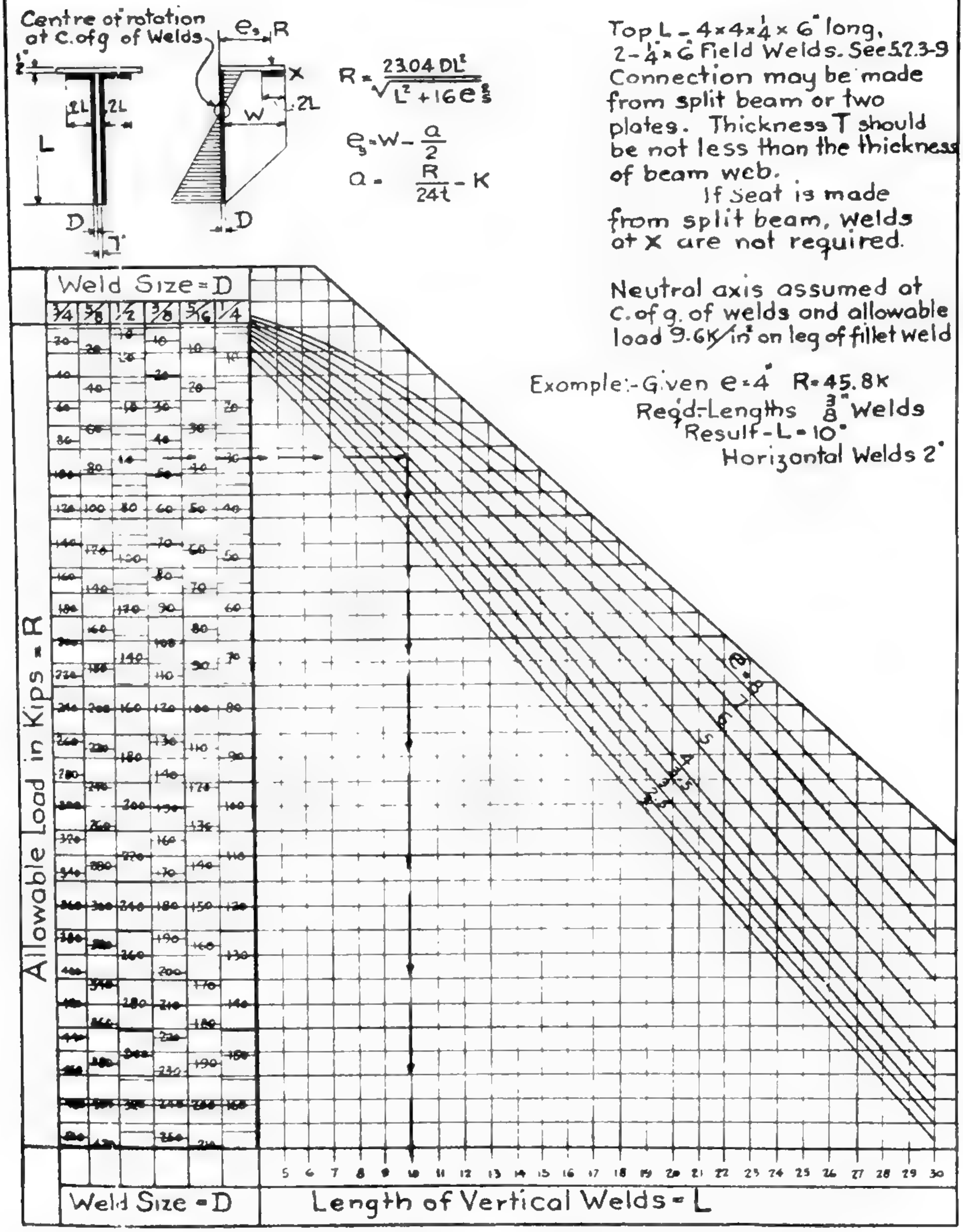
Table 5—Allowable Loads on Unstiffened Seats



See AISC Manual for *t* and *k*. Determine *ef* from diagrams in Table 4. Enter top diagram of this table with *ef*, *R* and *W* and find *T*. Enter bottom diagram on this table with *ef* and *R*, and choose suitable mutually related values for *A* and *D*.

Horizontal leg of seat angle must be greater than *a* and also it must be greater than the 2½-in. weld length for attachment of bottom flange of beam. The length of horizontal leg of angle could be increased if desired, but length of vertical leg must be 5 in. for a ¼-in. weld size in the example shown above.

Table 6—Allowable Loads on Stiffened Seats for Horizontal Weld Lengths of 0.2*L* on Each Side of Stem



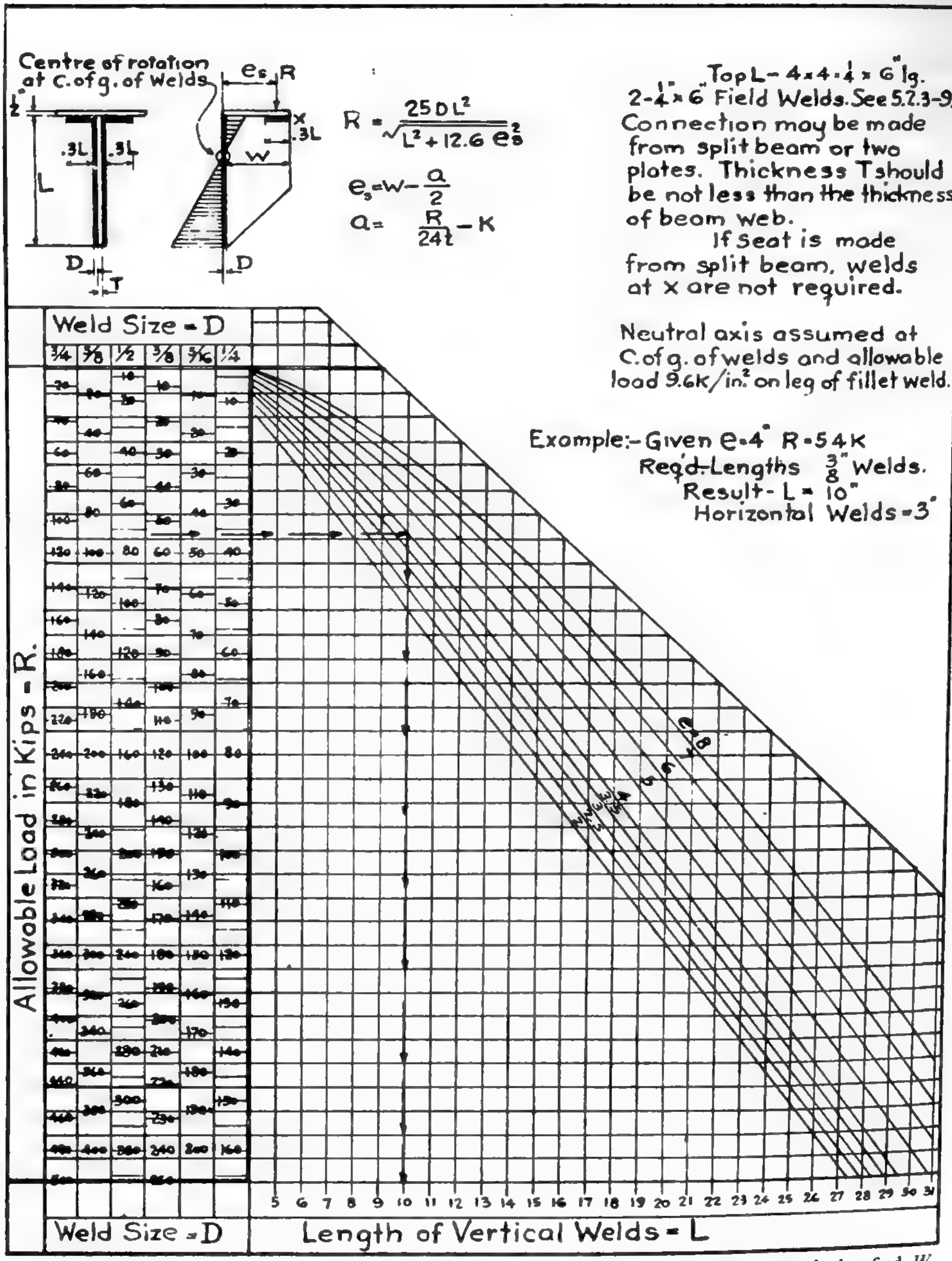
See AISC Manual for *t* and *k*. Determine e_s and *a* from diagram in Table 4, and also find *W* as dimensioned there for a stiffened seat.

Enter diagram in this table with *R*, *D* and e_s and find length *L* for vertical welds.

For flexible connections, use top angle 4 x 4 x 6 in. long and two ¼- x 6-in. field welds as shown in Fig. 9.

When seat is used for a restrained connection and *W* is not great enough to accommodate welding of bottom flange of beam to the seat, the horizontal element of the seat may be increased to overhang the stem, and its thickness may have to be increased also

Table 7—Allowable Loads on Stiffened Seats for Horizontal Weld Lengths of 0.3L on Each Side of Stem



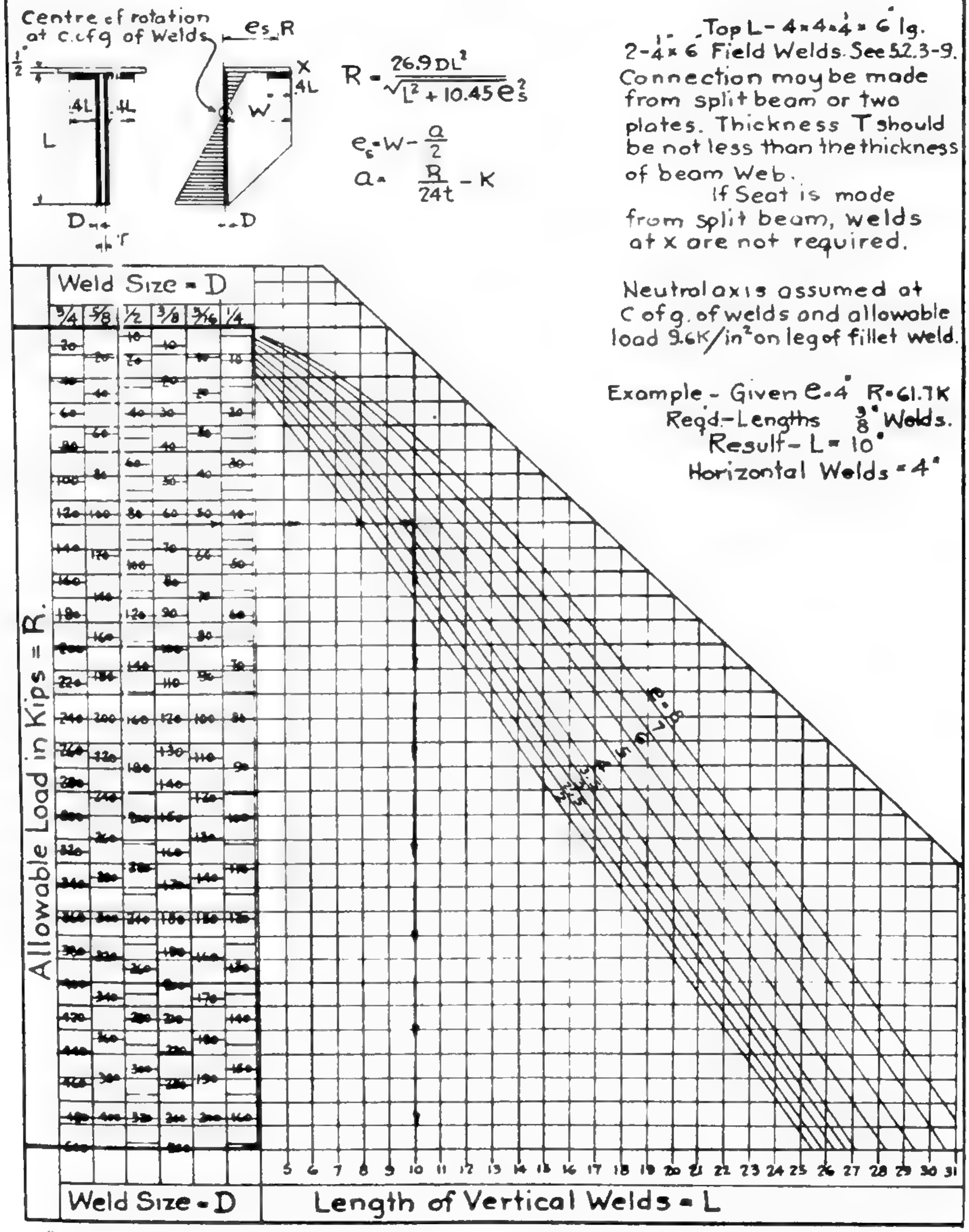
See AISC Manual for t and k. Determine e_s and a from diagram in Table 4, and also find W, as dimensioned there for a stiffened seat.

Enter diagram on this page with R, D, and e and find length L for vertical welds.

For flexible connections, use top angle 4 x 4 x 1/4 x 6-in. long and two 1/4 x 6-in. field welds as shown in Fig. 9.

When seat is used for a restrained connection and W is not great enough to accommodate welding of bottom flange of beam to the seat, the horizontal element of the seat may be increased to overhang the stem, and its thickness may have to be increased also.

Table 8—Allowable Loads on Stiffened Seats for Horizontal Weld Lengths of 0.4L on Each Side of Stem



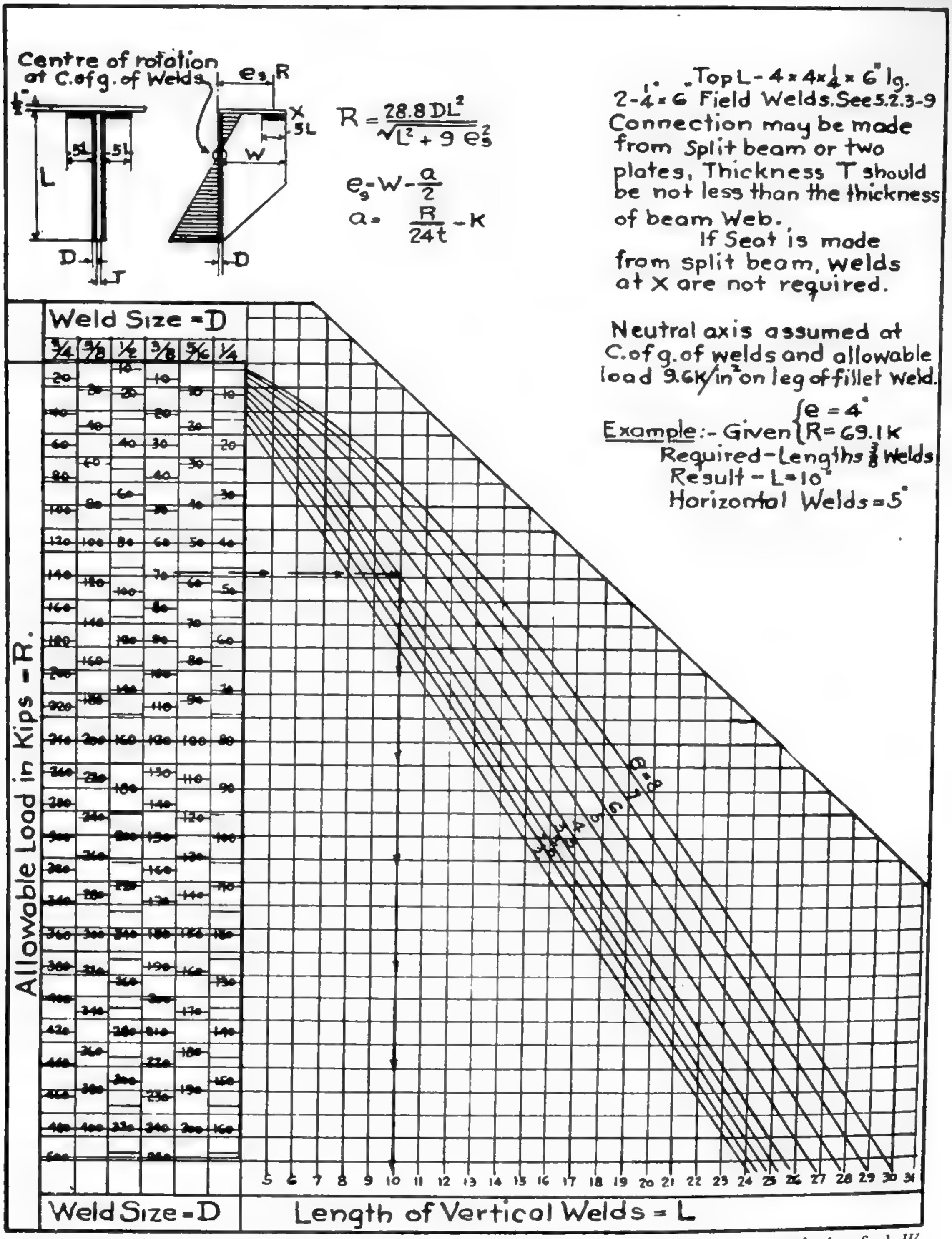
See AISC Manual for *t* and *k*. Determine e_s and *a* from diagram in Table 4, and also find *W* as dimensioned there for a stiffened seat.

Enter diagram in this table with *R*, *D* and e_s and find length *L* for vertical welds.

For flexible connections, use top angle 4 x 4 x ¼ x 6-in. long and two ¼ x 6-in. field welds as shown in Fig. 9.

When seat is used for a restrained connection and *W* is not great enough to accommodate welding of bottom flange of beam to the seat, the horizontal element of the seat may be increased to overhang the stem, and its thickness may have to be increased also

Table 9—Allowable Loads on Stiffened Seats for Horizontal Weld Lengths of 0.5*L* on Each Side of Stem.



See AISC Manual for *t* and *k*. Determine e_s and *a* from diagram in Table 4, and also find *W* as dimensioned there for a stiffened seat.

Enter diagram on this page with *R*, *D* and e_s and find length *L* for vertical welds.

For flexible connections, use top angle 4 x 4 x 1/4 x 6-in. long and two 1/4 x 6-in. field welds as shown in Fig. 9.

When seat is used for a restrained connection and *W* is not great enough to accommodate welding of bottom flange of beam to the seat, the horizontal element of the seat may be increased to overhang the stem, and its thickness may have to be increased also.

dimensions; which though it results in rather involved formulas, does however lend itself to the development of groups of curves which may be employed for the rapid check of values of assumed weld groupings. The results may be checked analytically as follows; first determining the unit stress due to shear by dividing the total load by the total inches of weld; then determining the unit shearing stress in the welds due to moment, by computing the moment and dividing by the polar moment of inertia of the weld group over the distance from the neutral axis to the extreme weld; and finally combining these values vectorially to obtain the maximum combined unit stress.

Design of Connections (Simple Beams)

While the use of the charts for the solution of the stresses in various weld combinations should present no problem, a short description of the method of application of the charts to the design of some of the more common connections is probably desirable.

For simple framing the diagram in Table 2 generally is adequate to cover the simple cases. Should the field weld be such that the designer deems an independent design necessary it will be noted that the field weld on each angle is a special case of the weld in Table 3 where $a = k$.

For an unstiffened seat it is first necessary to determine the web thickness t and dimension k from the AISC Manual or from a steel shape book, then employing Table 4 to determine cf for use in Table 5 for the solution of angle size, thickness, length and weld size. Similarly the factor c_t may be determined for stiffened seats, together with the necessary projection W. Tables 6 to 9 may then be used for various proportions of horizontal to vertical welds in determining the design of the connection.

The top connection used with either of the above seats is fairly well standardized. Where a rather flexible connection is required the 4 × 4 × $^1/_4$-in. angle, 6 in. long, indicated in Fig. 9 (sketch *A*) is used. It is shipped loose and field welded with continuous $^1/_4$-in. fillet welds on the two toes. For beams with flanges 4 in. or less in width, 4-in. long angles are used.

The framing angle, unstiffened and stiffened seats described above have been standardized* and a system of piece-marks developed and combined with beam safe load tables in a manner which greatly simplifies the selection of connections for simple beams. While the inclusion of such tables in this HANDBOOK would be very desirable, space limitations make it impractical. Figures 6, 7 and 8 indicate the basic system, the method of detailing for the shop and a typical page from the safe load tables. (Full tables are available in the *Manual of Design for Arc-Welded Steel Structures*.)

Another form of top connection, considered suitable for use with the above seats, employs a plate connected to the column by a full section butt weld designed to develop 25% of the resisting moment of the beam for which condition the unit stress in weld and plate is limited to 20 ksi.‡ at the column, but the section is then reduced as indicated in Fig. 9 (sketch F) so that at the reduced area the corresponding unit stress would be 32 ksi. It is desirable to leave an unwelded length of reduced section plate as indicated to provide adequate material for plastic behavior. Care should be taken in the transition area to reduce the possibility of notch effect, especially when the joint may be subjected to plastic flow at low temperature.

Design of Connections (Rigid, Semi-Rigid, Wind Bracing)

Variations of the top plate connection are applicable to rigid, semi-rigid and wind-bracing connections. Generally the plate is of constant width, as indicated in Fig. 9 (sketch E) though a variation is used when the plate is fillet-welded to the column as shown in Fig. 9 (sketch J).

When designed for *rigid framing* the plate and the welds are proportioned to carry the calculated moment within the stress limits of the Specification and it is assumed that deformation of weld or plate is within the elastic range. The connection between the bottom flange of the beam and the beam seat must be designed to transmit its component share of the moment couple to the column and if the moment at the joint may be reversed under another combination of loading, the seat must be connected to the

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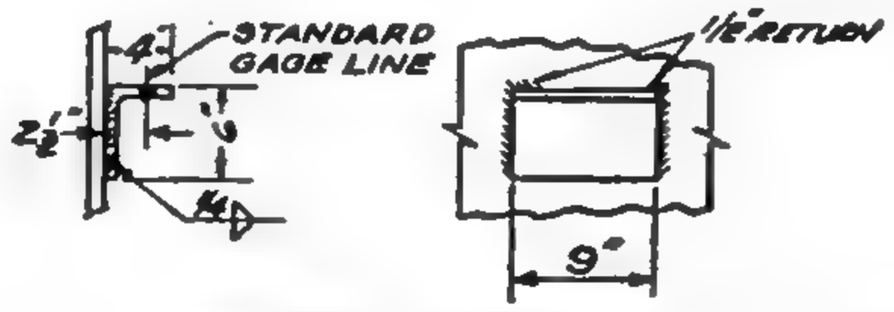
* Adopted as Standard by the Canadian Standards Association, 1948.
‡ kips (1000 lb.) per sq. in.

TYPICAL EXAMPLES

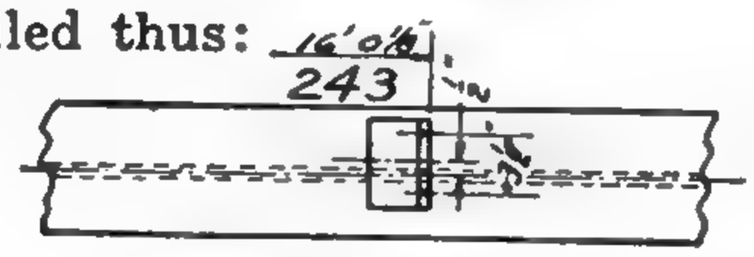


‡ See note below

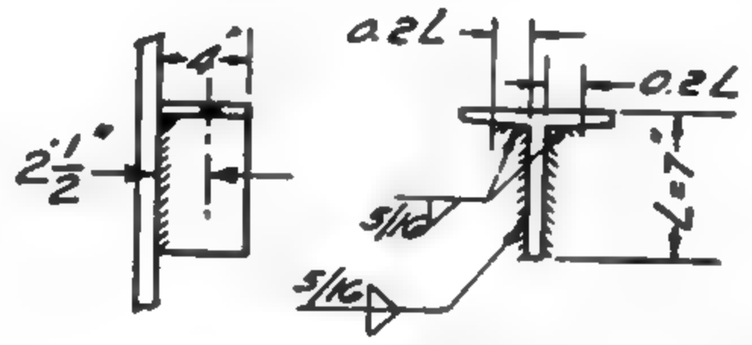
243

200 Designates ¼" Fillets
40 Designates 6 x 4 x ⅝" ∟
3 Designates 9" Length.

Detailed thus:



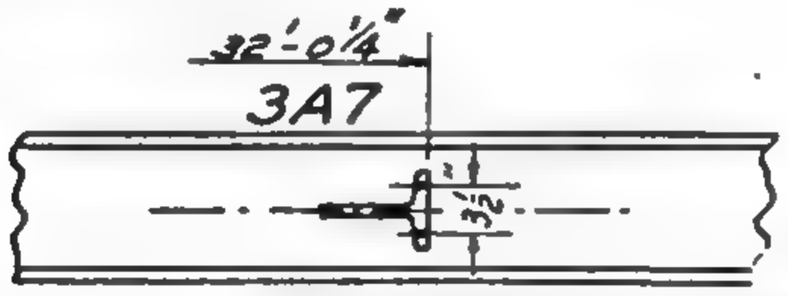
*See note below regarding sizes of welds.



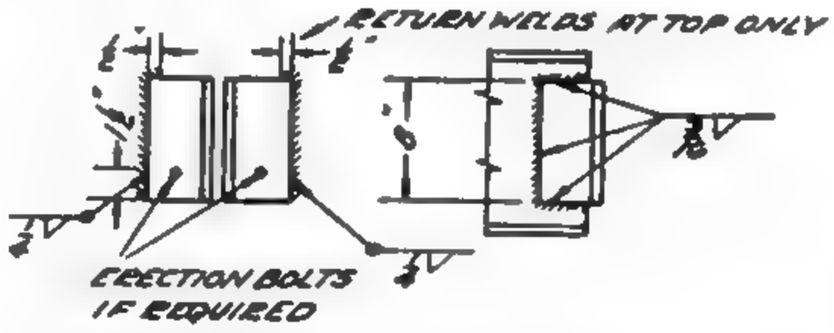
3A7

3 Designates ⅝ Fillets
A Designates 4" Seat
7 Designates Half 14 WF43

Detailed thus:



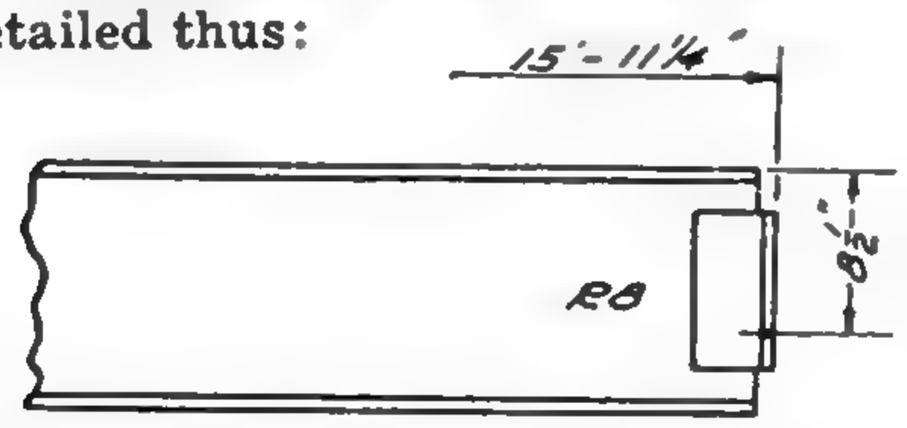
*See note below regarding sizes of welds.



R8

R Designates 2 ⌋[s 3½ x 2½ x ¼
8 Designates 8" Length
R Designates Weld Sizes Also.

Detailed thus:



*See note below regarding sizes of welds.

*When the thickness of material of the supporting members, to which beam-seats or framing angles are to be welded, exceeds the maximum permissible thickness for use with the weld sizes indicated by the piecemarks for the standardized connections, the size of weld must be increased. The framing angles listed in the beam safe-load tables, and the shop welds for them, have been increased where necessary, to provide weld sizes that comply with minimum size requirements.

‡When the flange of a column is narrower than a seat angle that is to be welded to it, use same vertical welds to join back of seat angle to toes of column flange.

Fig. 6.—Details of Standardized Welded Connections

MEANING OF PIECE MARKS

⌜ ANGLE SEATS

Mark	Weld	Mark	Angle Size	Mark	Length
100	3/16	10	3½ x 3½ x 3/8	1	4½
200	¼	20	4 x 3½ x ½	2	6½
300	5/16	30	5 x 3½ x 5/8	3	9
400	3/8	40	6 x 4 x 5/8	4	11
500	7/16	50	6 x 4 x ¾	5	13
600	½	60	7 x 4 x ¾	6	15
700	5/8	70	7 x 4 x ⅞	7	17
800	¾	80	8 x 4 x 1	8	20
900	⅞	90	†8 x 6 x 1⅛	9	24
9a00	1				
9b00	1⅛				

T TEE SEATS

Mark	Weld	Mark	Seat	Mark	Material
1	3/16	A	4	5	Half 10 WF 21
2	¼	B	5	6	" 12 WF 36
3	5/16	C	6	7	" 14 WF 43
4	3/8	D	7	8	" 16 WF 58
5	7/16	E	8	9	" 18 WF 77
6	½	F	9	9w	" 18 WF 96
7	5/8	G	10	10½	" 21 WF112
8	¾	H	12	12	" 24 WF160
9	⅞	J	15	13½	" 27 WF177
9a	1			15	" 30 WF190
9b	1⅛			16½	" 33 WF220
				18	" 36 WF260

⌝⌜ FRAMING ANGLES

Mark	Angle Size	Mark	Angle Length	Mark	Angle Length
R	3½ x 2½ x ¼	2½	2½	8	8
S	3½ x 2½ x 5/16	3	3	9	9
T	3½ x 2½ x 3/8	4	4	10	10
2R	3½ x 2½ x ¼	5	5	11	11
2S	3½ x 2½ x 5/16	6	6	12	12
2T	3½ x 2½ x 3/8	7	7	Etc.	

STANDARDIZED WELD SIZES

Mark	Shop	Field	Mark	Shop	Field
R	3/16	¼	2R	¼	¼
S	¼	5/16	2S	5/16	5/16
T	5/16	3/8	2T	3/8	3/8

† If 8 x 6 x 1⅛-in. angle is not available, make this angle seat from an 8 x 8 x 1⅛-in. angle.

Fig. 7—Details of Standardized Welded Connections

column for the full stress produced by this moment. It is assumed that this connection develops 100% rigidity.

For *semi-rigid framing* the design of the connection is similar to that for rigid framing except that the degree of restraint produced by the connection is that which has been established by test for the particular type of joint under consideration.

loading. The welds connecting the top plate to column and beam are designed at normal unit stress to develop the value of the plate at the increased allowable stress for wind loads. The connection to the seat is designed for the same moment couple at corresponding values for the material and welds. It is assumed that any combination of gravity and wind

16″ WIDE FLANGE SECTIONS

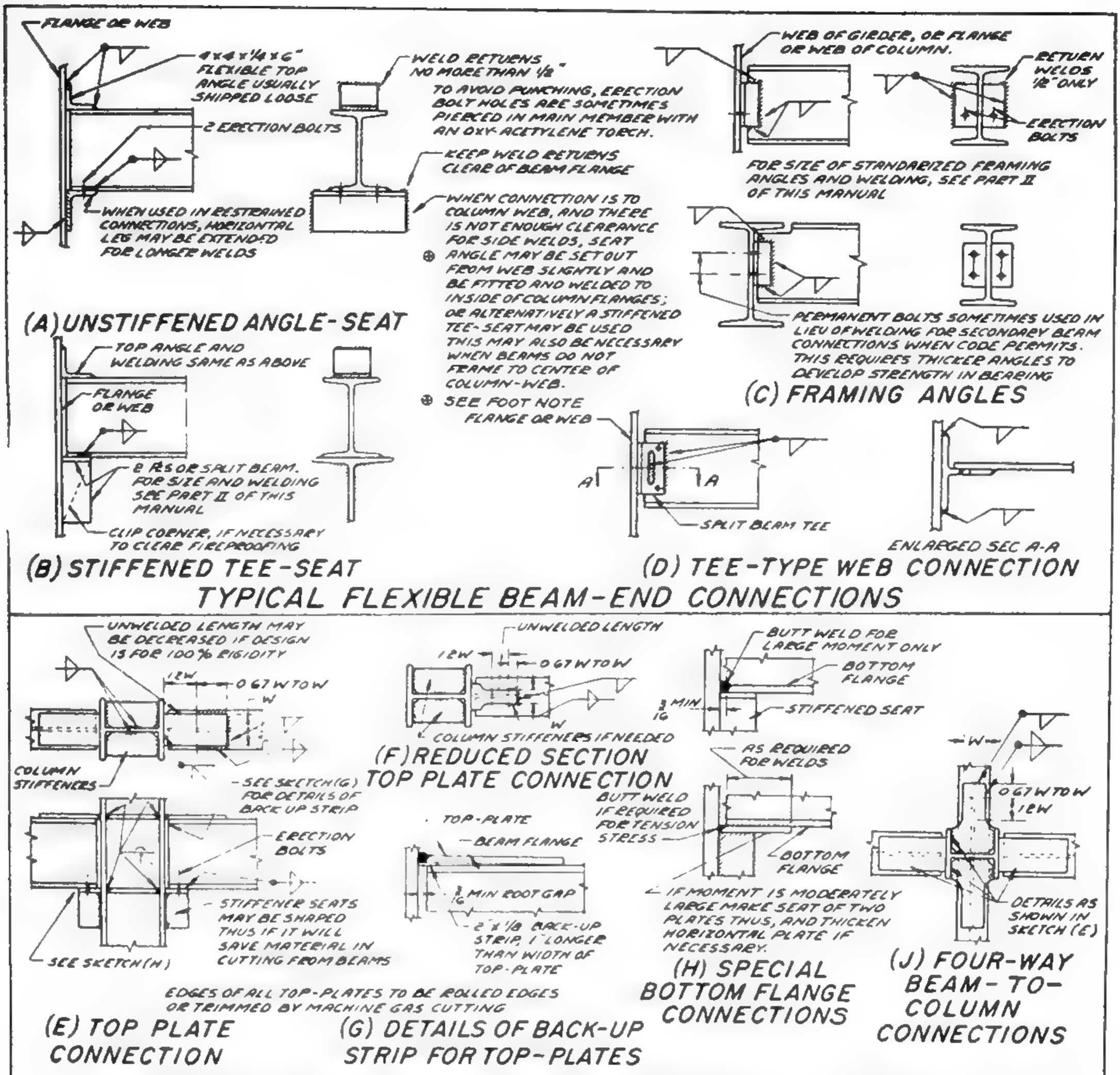
Allowable Uniform Loads in Kips for Beams Laterally Supported. Piece Marks of Standardized Welded Connections

Span in Feet	Nominal Depth and Width—Weight per Foot: 16 x 7 — 50 — Details ⌐T	⌐	T	Load	45 — Details ⌐T	⌐	T	Load	40 — Details ⌐T	⌐	T	Load	36 — Details ⌐T	⌐	T	Load	Deflection Inches
			6E13½	160	T14		6E13½	146	T14		5E13½	128	S14		5E13½	124	
7			"	154	"		5D13½	138	S14		"	123	"		4D12	107	.06
8	T14		5D13½	135	S14		4C12	121	R14		4D12	107	R14		4C10½	94	.08
9	S14		4C12	120	"	898	"	107	"		"	95	R13	695	4B9	83	.11
10	"	898	"	108	R14	796	4B10½	97	R13	796	4B10½	86	R12	593	"	75	.13
11	R14	796	4B10½	98	R13	694	"	88	R12	694	4B9	78	R11	493	3A9	68	.16
12	R13	694	"	90	R12	593	4A9	80	"	593	"	72	"	"	3A8	63	.19
13	"	593	4A9	83	"	483	"	74	R11	493	3A9	66	R10	383	"	58	.22
14	R12	"	"	77	R11	"	3A9	69	"	383	"	61	"	373	"	54	.25
15	"	483	3A9	72	"	383	"	64	R10	"	3A8	57	R9	363	"	50	.29
16	R11	383	"	67	R10	"	"	60	"	373	"	54	"	353	"	47	.33
17	"	"	"	63	"	363	"	57	R9	"	3A7	51	"	"	"	44	.37
18	R10	"	"	60	"	"	"	54	"	263	"	48	"	343	3A7	42	.42
19	"	363	"	57	R9	"	3A8	51	"	"	"	45	R8	243	"	40	.47
20	"	"	"	54	"	263	"	48	"	"	"	43	"	"	"	38	.52
21	R9	"	3A8	51	"	"	"	46	R8	"	"	41	"	"	"	36	.57
22	"	263	"	49	"	"	"	44	"	243	"	39	"	233	"	34	.63
23	"	"	"	47	"	243	"	42	"	"	"	37	R7	"	"	33	.68
24	"	"	"	45	R8	"	"	40	"	"	"	36	"	"	"	31	.75
25	"	243	"	43	"	"	"	39	"	233	"	34	"	"	2A7	30	.81
26	R8	"	"	41	"	"	"	37	"	"	"	33	"	"	"	29	.87
27	"	"	"	40	"	"	"	36	"	"	"	32	"	"	"	28	.94
28	"	"	"	38	"	"	"	35	"	"	"	31	"	"	"	27	1.01
29	"	"	"	37	"	"	"	33	"	"	"	30	"	"	"	26	1.09
30	"	"	"	36	"	"	"	32	"	"	"	29	"	"	"	25	1.16
31	"	"	"	35	"	"	"	31	"	"	"	28	"	"	"	24	1.24
32	"	"	"	34	"	"	"	30	"	"	"	27	"	"	"	24	1.32
33	"	"	"	33	"	"	"	29	"	"	"	26	"	"	"	23	1.41
34	"	"	"	32	"	"	"	28	"	"	"	25	"	"	"	22	1.50

Fig. 8.—Typical Safe Beam Loads for Standardized Welded Connections

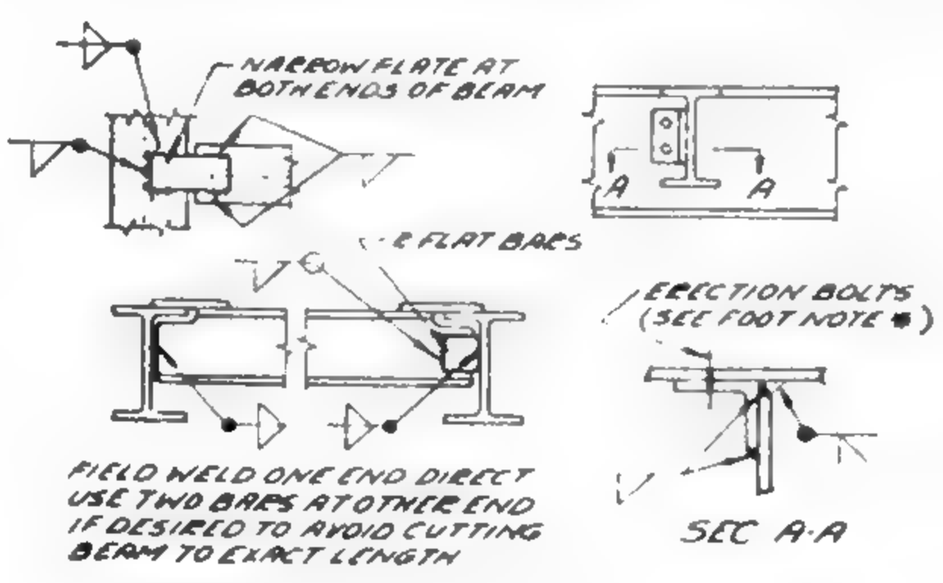
For *wind-bracing connections* in a structure designed as a simple frame the top plate is designed to carry the calculated wind moment at the usual stress permitted by the Specification for such

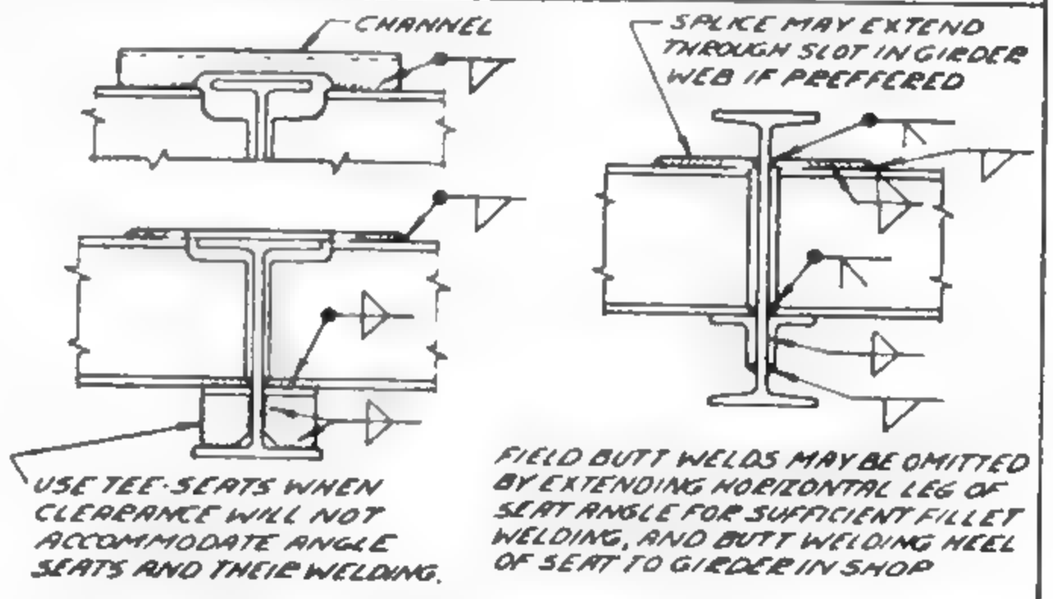
loading which would produce a total stress in the connection exceeding the yield point, would be relieved by plastic flow in the unwelded area in the top plate. Since the moment due to gravity



TYPICAL FLEXIBLE BEAM-END CONNECTIONS

TYPICAL RIGID SEMI-RIGID AND WIND BRACING CONNECTIONS





All top plates should be trimmed and cut to shape by machine oxygen cutting or carefully guided manual oxygen cutting, to avoid rough or damaged edges as caused by shearing.

Although some tests of top plate connections have involved interior reinforcing plates simulating the constraint at a four way connection (sketch J, above), no tests have been made with all four of the connections loaded simultaneously.

Fig. 9.—Typical Beam and Girder Connections

load in the simple frame is not reversible, no provision need be made in the seat for plastic behavior.

The effect of a reversal of the direction of beam end rotation upon the top plate after it has gone through a cycle of loading which has produced plastic flow, is to reduce the tension from yield point stress to some lower value, which may result in appreciable compression in the top plate. Where such a condition may be expected to occur the top plate should be made thick enough to prevent buckling under compression. This may be accomplished by making the thickness not less than one twenty-fourth of the clear distance between the end welds. It is not considered that repeated cycles of tension and compression in building construction would occur often enough in the life of the structure to result in conditions requiring a consideration of the endurance limit of the material.

In all applications employing top plates connected to columns by butt welds the backing plate shown in Fig. 9 (sketch G) represents the most efficient method for obtaining full butt weld values under field conditions.

The various connections shown in the remaining sketches of Fig. 9 and those in Fig. 10 demonstrate those described in the paragraphs above, as well as some suggestions for spandrel connections and variations of the more standardized types.

Columns

Splices.—Milled column splices in tier buildings ordinarily require only a nominal amount of welding to hold the parts securely in place, since the load is transferred directly through the contact surfaces and the spliced shafts are stayed laterally by the floor framing.

Such a splice is indicated in Fig. 11 (left side detail). It is obvious that such a splice is applicable only where the difference in depth of the adjoining sections is small. Where the difference in depths results in a space between splice plate and column flange exceeding $^1/_8$ in., direct welding is impracticable unless the space is great enough to permit the use of filler plates of adequate thickness to transfer the stress from plate to filler plate to column flange. This doubles the amount of welding, one disadvantage of the use of fills in welded construction.

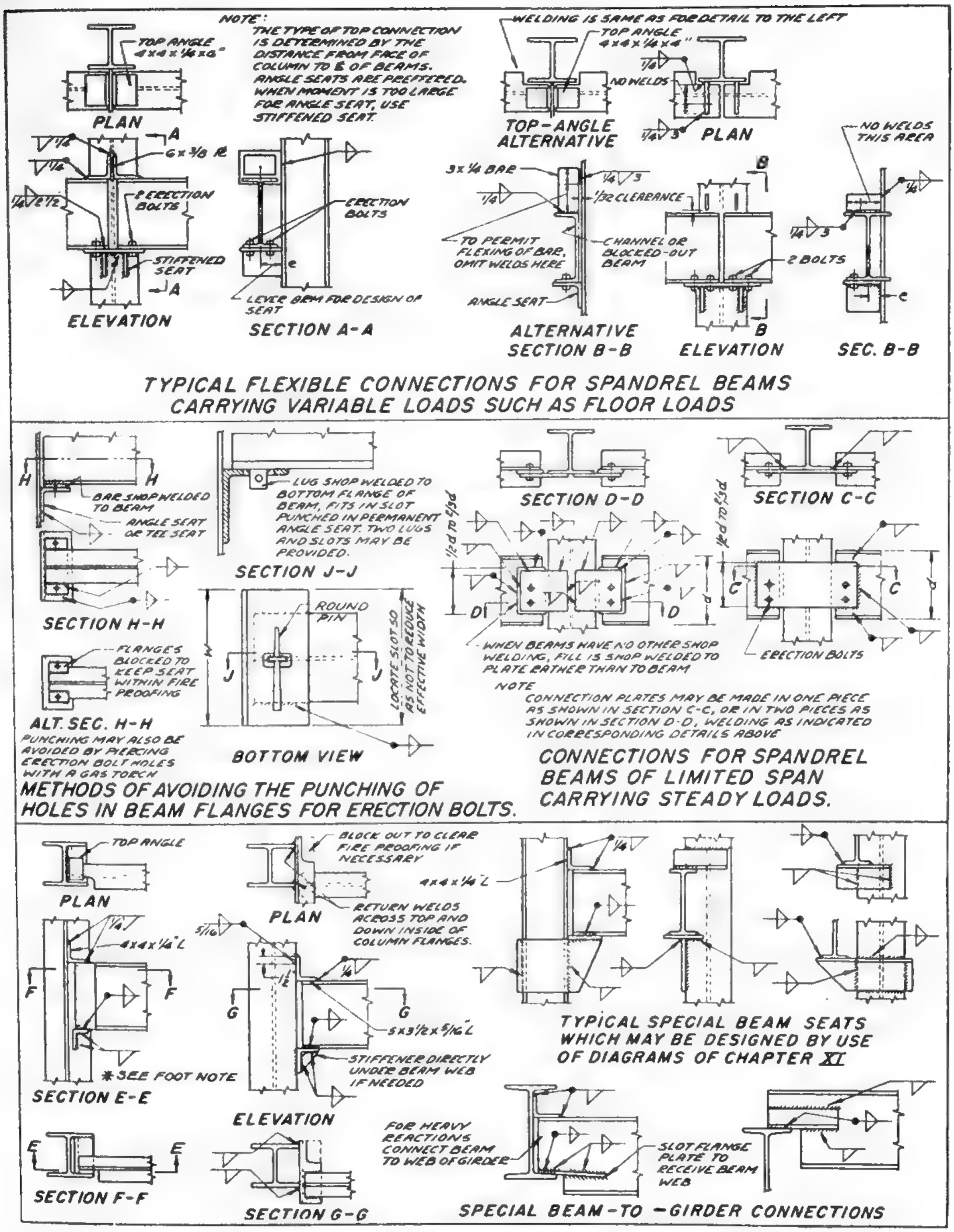
A form of splice which has a greater range of application is that indicated in the right-hand sketch of Fig. 11. The thickness of butt plate is usually made $^1/_2$ or $^3/_4$ in. for columns of the same nominal depth and two inches for columns differing by two inches in depth. The required thickness may be more accurately determined by the bending stress in the plate when transferring the load from the flanges of the upper to the flanges of the lower shaft.

Column splices, remote from horizontal framing capable of affording lateral support, should be designed to provide a degree of continuity past the splice. The Code requires the splice in such cases to transmit 50% of the axial column load. The Code also requires that adequate welding be provided to care for any net tension across the spliced plane resulting from wind forces acting in conjunction with 75% of the dead loading and no live loading, provided this condition of loading produces the greatest net tension.

Base Plates.—The welding, if any, required at a simple column base plate, need be sufficient only to hold the column in place. (See Fig. 12.) On light columns with moderate size base plates, it is customary to attach the plate directly to the column in the shop. Where it is deemed desirable for any reason to level up and grout the plates in place prior to erection of the columns, base angles with holes located to accommodate anchor bolts are shop welded to the column shafts, and no field welding of base angles to base plates is required.

Where the column design is predicated upon a definite amount of transfer of horizontal shear or moment to the foundation, as is frequently the case in rigid frames and certain types of mill building columns, the base detail must be designed for this shear and moment without sensible distortion in the detail parts.

Crane Column Splices.—Figure 13 indicates typical crane column splices. Section C-C indicates the use of slotted holes to permit longitudinal movement at the end of the crane girder so as not to limit girder deflection. This is a detail of design, deserving more serious attention than it usually receives. Unless the crane girders are spliced over the support for continuity the connection which transmits the side thrust from the top of the girder to the column must be designed to permit rather free longitudinal movement



TYPICAL FLEXIBLE CONNECTIONS FOR SPANDREL BEAMS CARRYING VARIABLE LOADS SUCH AS FLOOR LOADS

METHODS OF AVOIDING THE PUNCHING OF HOLES IN BEAM FLANGES FOR ERECTION BOLTS.

CONNECTIONS FOR SPANDREL BEAMS OF LIMITED SPAN CARRYING STEADY LOADS.

Fig. 10.—Miscellaneous Special Beam-End Connections

of the girder at this point, while providing for the necessary transmission of side thrust.

Plate Girders

Plate girder construction offers one of the most attractive applications for cost reduction by use of welding. This is especially true for those shops not equipped with multiple punches, multiple drills, pit-riveters and such highly mechanized methods which produce low-cost riveted fabrication. The greater simplification possible by welded plate

girder construction results not only in an appreciable saving in material with the consequent saving in cost, but also a saving in fabrication costs as well. Where in riveted construction a truss may be more economical than a plate girder for a definite span and condition of loading, it may be that the relative costs in welded construction would favor the plate girder.

Welded plate girders of moderate size are composed of a web plate, fillet welded to two flange plates, with flat bar stiffeners, where required, fillet welded to web and flanges. See Fig. 14.

For heavier plate girders, where the distribution of loads produces variations in flange stress, making it economical to vary the flange area, it is usual where more than one cover plate would be required, to use flange plates of various thicknesses butt welded end to end. The use of multiple plates fillet welded together is uneconomical since at each plane the welds must connect for the proportion of the stress carried by the material beyond that plane, resulting in considerable increase in welding. This is the same characteristic of welded construction which makes the use of filler plates uneconomical.

Where a single pair of cover plates welded to a rolled beam section is adequate to carry the load such a section will generally be cheaper than a plate girder.

For the welded plate girder both flange and web splices are made with full penetration butt welds. These welds may be ground flush if conditions require it or they may be left in the as-welded condition. Partial penetration butt welds are not permitted for such splices nor is the use of splice plates generally considered good practice. Since splice plates are attached with fillet welds having a permissible value of only 70% × 13,600 psi. in shear, and this welding is doubled by having to be transmitted into and then out of the splice plate, while a butt weld has a value in tension or compression equal to that of the base metal (usually 20,000 psi.) it should be obvious that the butt welded joint is about four times as efficient. In fact, splice plates are economical only where the stress across the joint is small, and the cross section of main material is large. If the stress in a butt-welded splice is lower than, say 5000 psi., it may be cheaper to use a fillet-welded splice plate.

The webs of building girders are designed to have a thickness not less than $^1/_{170}$ of the unsupported depth between flanges. When the ratio of this depth to the thickness h/t equals or exceeds 70, intermediate stiffeners are required at all points where V, the maximum unit shear in pounds per square inch, exceeds 64,000,000 divided by $(h/t)^2$. The clear distance, d, between such intermediate stiffeners may not exceed 11,000 $t/\sqrt{V}$.*

The thickness of the outstanding legs or projecting elements of flanges not supported against buckling must be not less than $^1/_{16}$ of their projection, when subjected to compression. If reducing the flange width will satisfy the above requirement, and the remaining flange is still adequate to satisfy design requirements, the flange need not be so reduced.

In some very heavy girders full penetration butt welds have been used to join the web to the flanges. Heavy tees have been used for flanges, employing butt welds between the tee stems and the webs, eliminating the cupping in the flange due

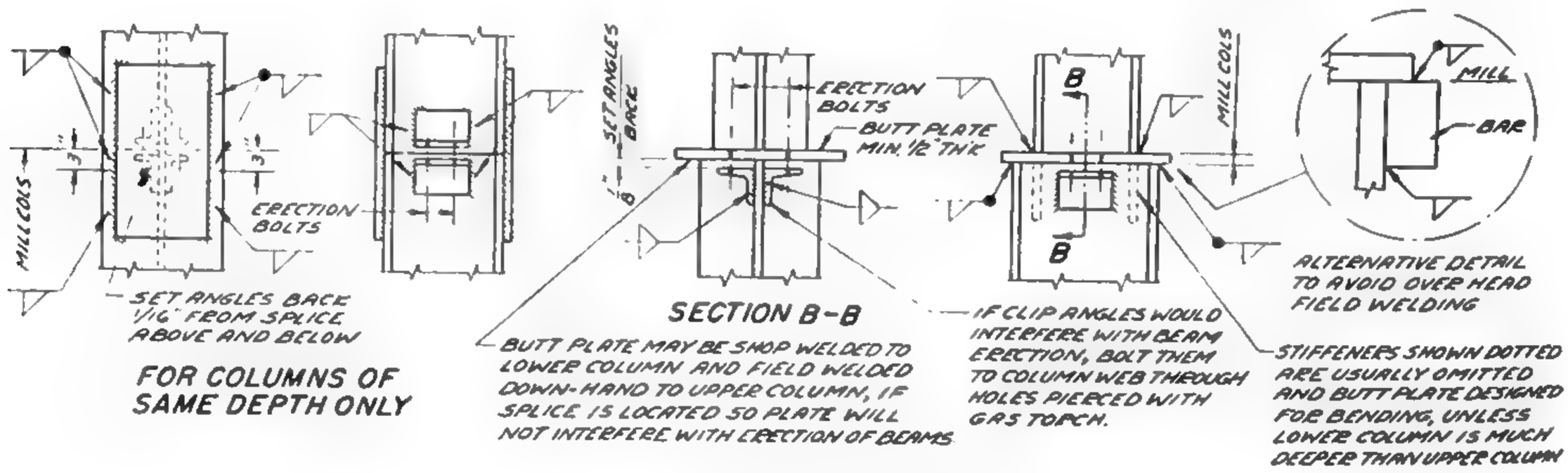


Fig. 11.—Typical Column Splices

* 84 in. max. in AISC Specifications.

to weld shrinkage. However, when the joint between flange and web is subjected to longitudinal shearing stresses only, it has not been demonstrated that butt welds offer any advantage over pairs of fillet welds. When this joint must transmit the stresses from heavy concentrations or rolling loads, or where the stress is so large as to require such large fillet welds as to be uneconomical, the use of butt welds is preferable.

When attaching a cover plate to a beam or girder, the transverse spacing of longitudinal welds must not exceed 32 times the thickness of the thinner plate joined (24 times in the case of crane girders, etc.). Should this spacing be exceeded on a thin cover plate, plug or slot welds are used to reduce the spacing to permissible limits.

If intermittent fillet welds are used spaced so that the ratio of weld length to total length is r, the nominal size, D, of each weld may be determined by the expression

$$D = \frac{H}{19.2r} = \frac{VQ}{19.2Ir}$$

$$\left(2 \text{ welds} \times 0.707 \times \frac{13{,}600}{1000} \text{ psi} = 19.2 \text{ ksi. per inch of weld size}\right)$$

The solution of the horizontal shear formula and the corresponding welding may be obtained by the use of the nomographic chart in Fig. 15; the combined stresses in the web from the chart, Fig. 16.

If the factors V, Q or I vary along the length of the girder, as is generally the case, separate calculations will be required for as many variations in the amount of welding as are warranted by considerations of economy in the welding operations and the layout costs involved in varying the spacing.

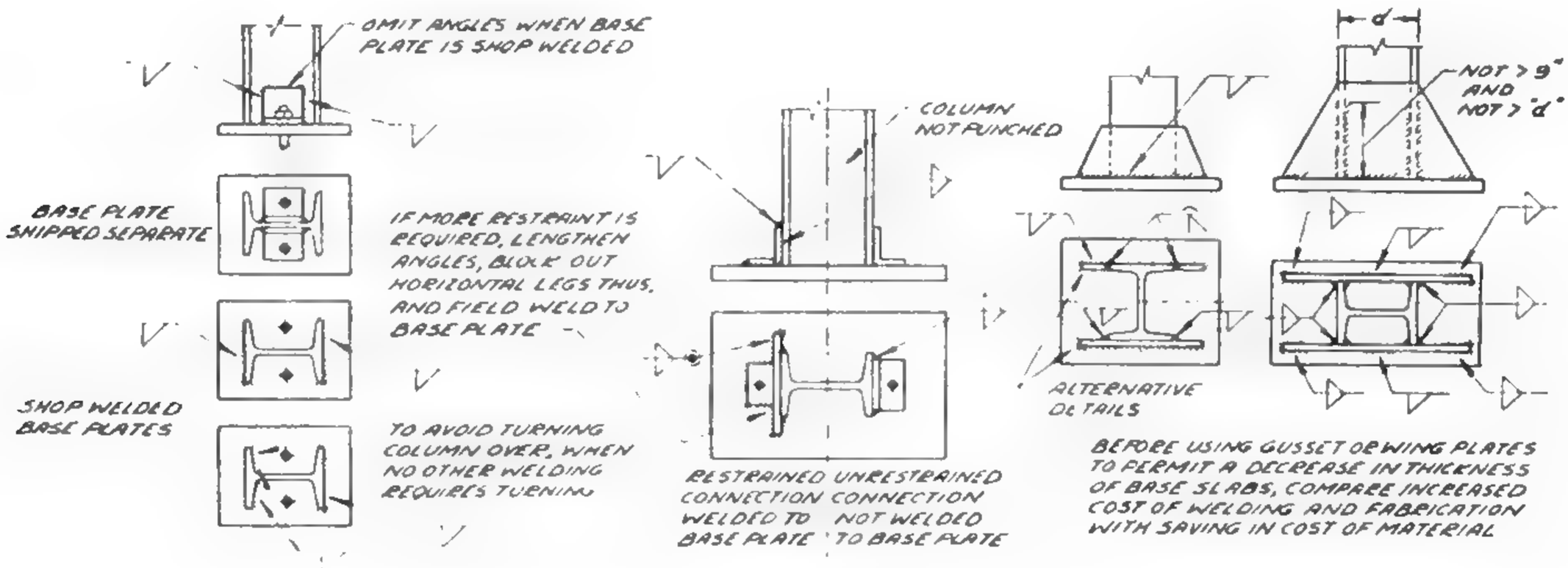


Fig. 12.—Typical Column Base Plate Connections

The amount of welding required between the flange plates of a girder and its web, or between any two component parts of the flanges, is determined in the conventional manner, by the horizontal shear per linear inch, H, which equals VQ/I where V is the total vertical shear at the section, Q is the static moment of that portion of the section which lies beyond the plane of the welded joint, and I is the moment of inertia of the entire cross section, both Q and I being taken about the neutral axis of the entire cross section. Multiplying the unit horizontal shear by twelve and dividing by the allowable weld stress per linear inch for a chosen weld size, gives the total inches required per foot of joint for the assumed weld size. For a pair of fillet welds the length of each weld is one-half the total obtained above.

Each cover plate is extended beyond the theoretical cut-off point a sufficient distance to accommodate enough continuous welding to develop the proportional part of the total flange stress that should be carried by that cover plate. In doing this, it is assumed that at the theoretical cut-off point, the stress in the girder flange without cover plates is the full permissible stress; and that the share of the total flange stress taken by the cover will be based on the following:

$$\frac{\text{Total stress in cover}}{\text{Total flange stress}} = \frac{S_2 - S_1}{S_2}$$

in which S_1 is the section modulus of the girder without the cover plates and S_2 is the section modulus with the cover plates.

Common practice is to weld the ends of the cover plates for their full value, using intermittent welding between the end welds of minimum size on the maximum spacing. The intermittent fillet welds should be sufficient to transmit the horizontal shear at any point. The welds at the ends of the cover plate, should be made continuous across the end of the plate and returned on each side a distance sufficient to develop the plate beyond the cut-off point. Tests indicate that the length of weld on the sides at the ends of a cover plate should be not less than one-half the plate width, nor more than the full plate width to provide good distribution of stress. The lengths of these welds are varied between the preferred limits to provide a reasonable weld size.

be used instead of intermittent fillets when more economical to do so or where it is considered advisable to seal the joint to prevent corrosion. It is good practice to use continuous welds in all cases where dynamic or repeated loadings may be of a degree which would make desirable eliminating even minor stress raisers. Tests of intermittent fillet welds indicate a lower fatigue resistance than is usual for continuous fillet welds under similar conditions.

The calculations for web stiffeners are made in much the same way as for riveted construction. Usually flat bars are used in place of angles, though for large concentrated loads inverted angles or tees are sometimes used. Non-bearing stiffeners are often attached to the webs only, cutting the ends on a bevel so that the flanges cannot bear on the stiffener. Where the stiffener is welded to the flange it is usually made sufficiently

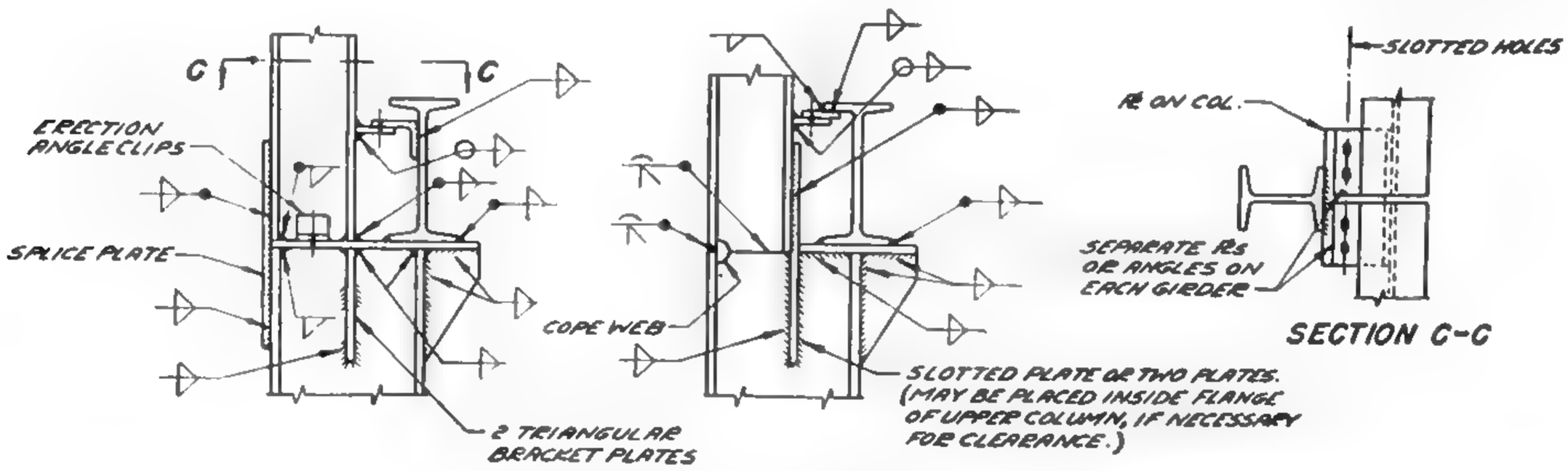


Fig. 13.—Typical Crane Column Splices

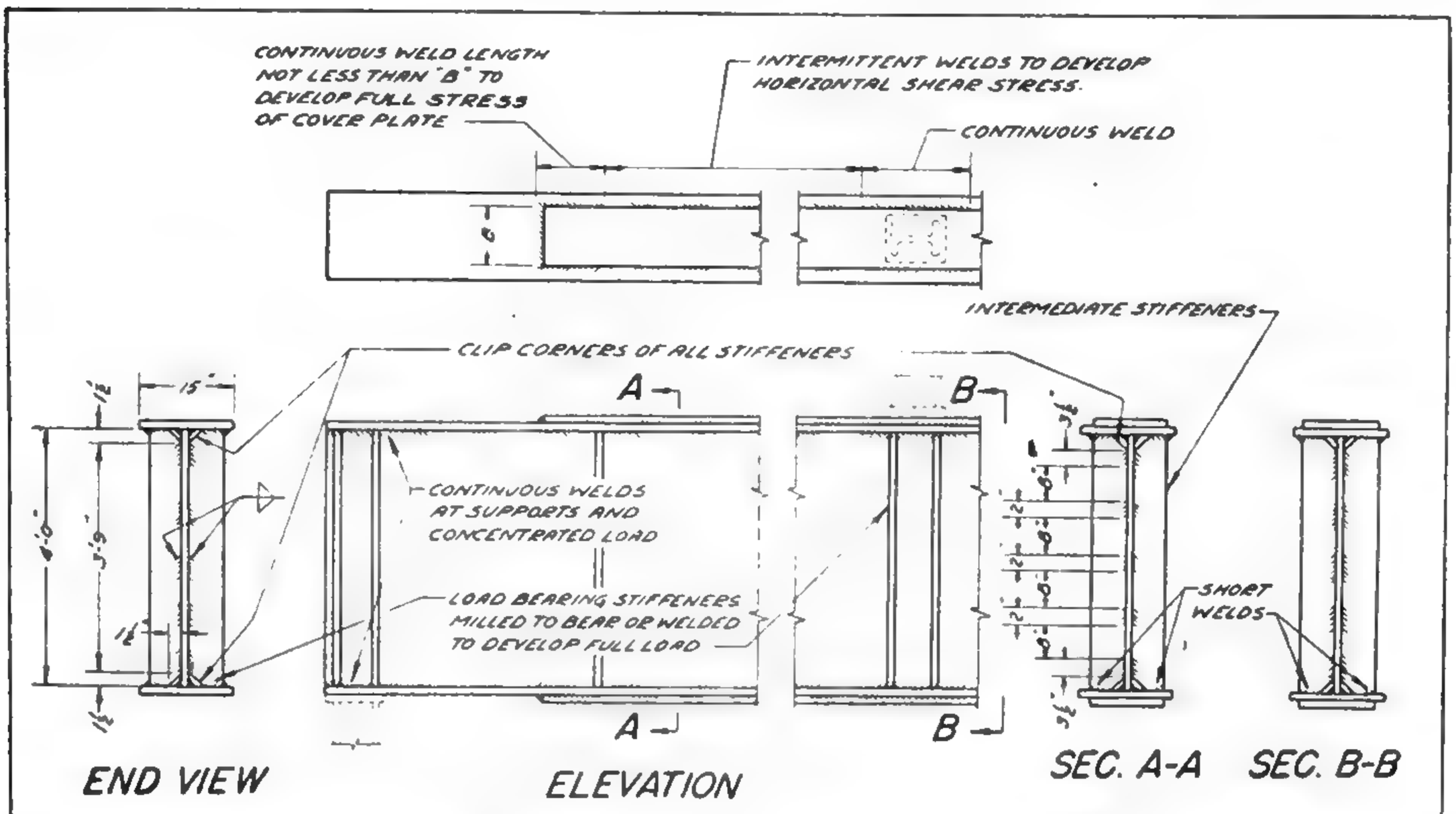
The minimum size of an intermittent fillet weld segment should be determined from the Code for the thicknesses of material involved and the lengths of the segments are usually at least 8 times the weld size, but in no case may be less than 4 times the weld size. The maximum clear distance between segments should not exceed 24 times the thinner part joined, in the case of tension elements, and 16 times in the case of compression elements, but in neither case more than 12 inches. For dynamic loading, the corresponding values are 14 and 10 times the thickness of the thinner part joined. At supports and at end points where there are large concentrations of stress, as at loads, ends of cover plates, etc., continuous welds should be used even though stress requirements would be satisfied by intermittent fillets.

Continuous welds of smaller size may

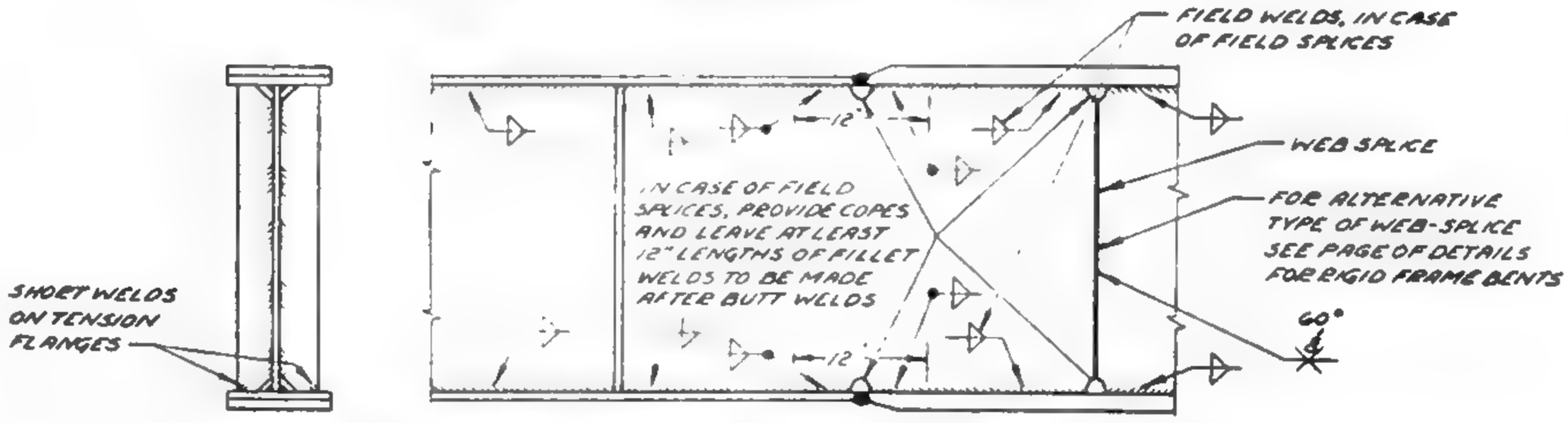
narrow so that the fillet weld around the stiffener will not come too close to the edge of the girder flange. It is preferable to have clearance of at least 3/8 in. between the edge of the weld and the flange. The thickness of non-bearing stiffeners is usually made about 1/16 their width, and the lengths and spacing of intermittent fillets are similar to the intermittent fillets used in welding flanges to webs or cover plates.

Load-bearing stiffeners are placed in pairs on the webs of plate girders at unframed ends and at points of concentrated loads. They are designed as columns assuming the column sections to comprise the pair of stiffeners and a centrally located strip of the web equal to not more than 25 times its thickness at interior stiffeners or a strip equal to not more than 12 times its thickness when the stiffeners are located at the end of the

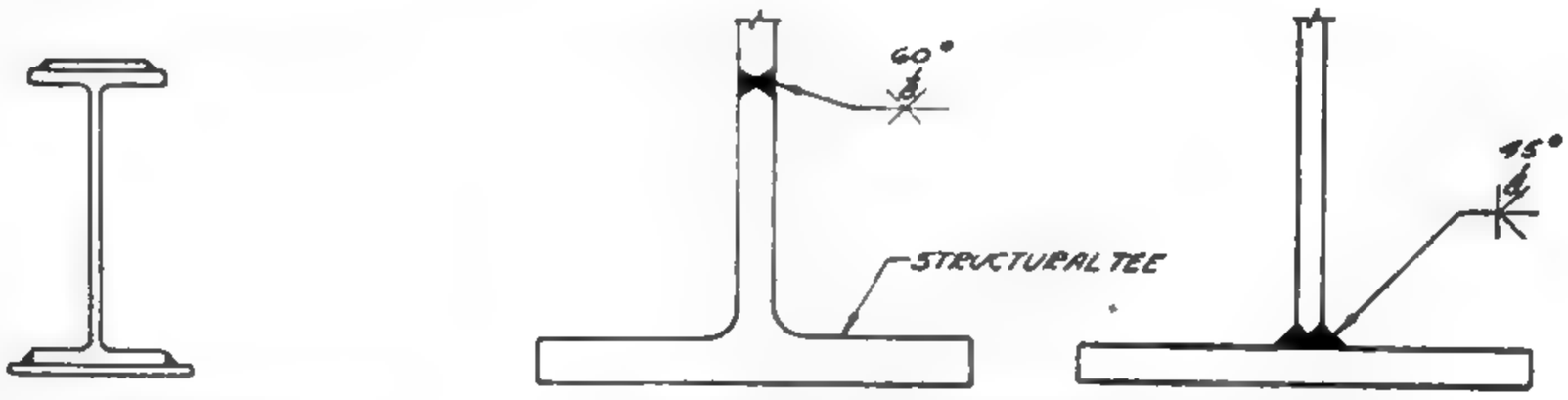
web. The column length is taken as not less than 3/4 of the length of the stiffeners in computing the ratio l/r. The ends of such stiffeners are not usually milled, unless the loads are of such magnitude that the size of fillet weld would become uneconomical. Where a large duplication of stiffeners would result in a low-unit cost for milling it may be more economical to mill and attach with nominal fillets than to use strength welds. In some cases it would be more economical



GIRDER FOR BUILDING CONSTRUCTION



ALTERNATIVE DETAILS FOR FLANGE PLATES



ROLLED BEAM WITH COVER PLATES

SPECIAL FLANGE DETAILS
(SELDOM USED IN BUILDING CONSTRUCTION)

NOTE
IN PRACTICE ALL WELDS SHOULD BE INDICATED BY STANDARD SYMBOLS. FULL CLARITY IS USUALLY POSSIBLE WITHOUT USE OF ANY SHADING.

Fig. 14.—Typical Girder Details

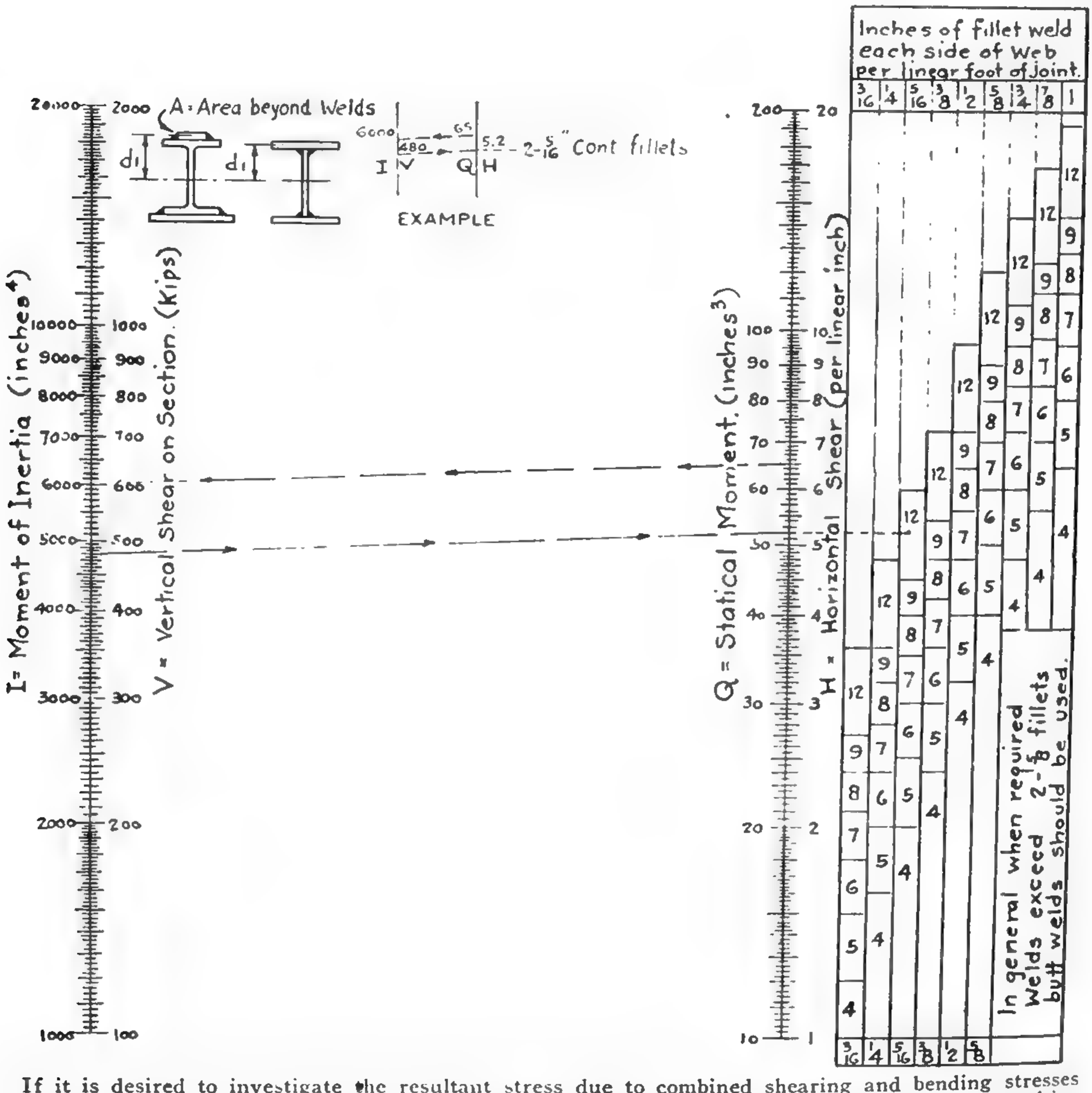
to bevel the ends of the stiffeners and butt weld them to the flanges.

Some specifications for dynamically loaded girders have prohibited or discouraged the attachment of stiffeners to the tension flange with transverse welds at points of high stress. Recent fatigue tests do not indicate as great a diminution in fatigue strength as was once believed to result when attachments are made to one side of a bar or plate.

It is generally accepted that the unframed ends of built-up welded flexural members should have end stiffeners where the depth or general proportions exceed those of rolled beam sections.

Trusses

Trusses may be broadly divided into two groups, the simple roof truss carrying fairly light loads on short or medium spans and the heavier type for longer spans and greater loads. The first type is fairly well standardized, generally having tee-chords made of split beam sections (WF Structural Tees) and web members of single angles or pairs of angles spaced at distances back to back



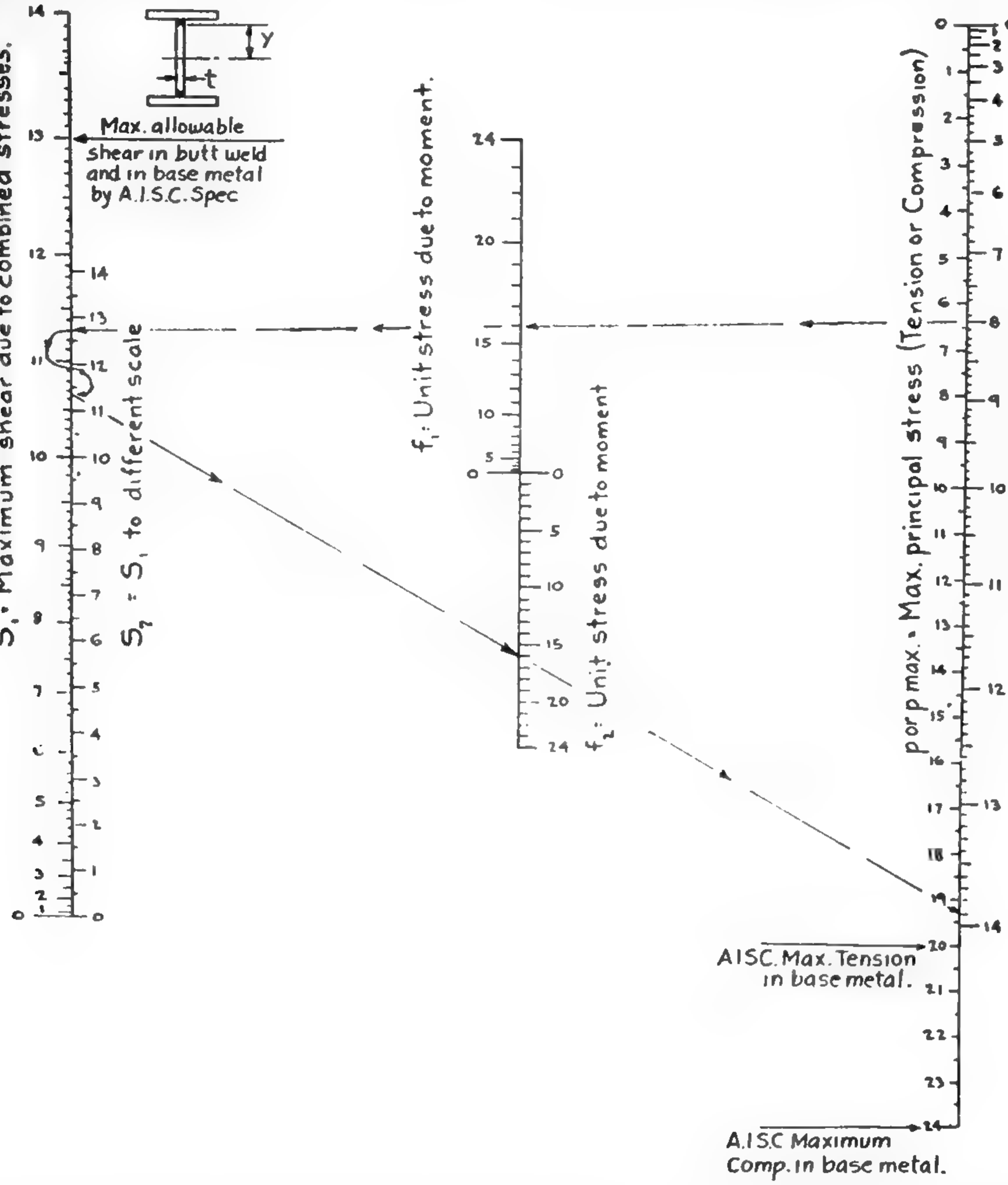
If it is desired to investigate the resultant stress due to combined shearing and bending stresses acting upon the fillet welds, with or without additional stress (normal to the bending stress) resulting from loads on flanges that are not carried by stiffeners and must be transmitted through the welds. the solution may be made by use of the diagram in Fig. 16, or the appropriate formulas after finding the value of *H* from the diagram on this page.

Fig. 15.—Welds Connecting Cover Plates or Webs to Flanges

(Proportioned for Horizontal Shear Only)

about equal to the thickness of the stems of the tee chords. Gussets are seldom required except possibly at the heels.

vertical plane. The ends of the web members are sawed or flame cut on a bevel and connected to the flanges of the chord



The AISC maximum compression of 24,000 psi. in base metal, as noted above, is for the special case of the web of a rolled section at the toe of fillet.

While this diagram is not needed for an independent check of butt welds when their allowable stresses are equal to full base metal values (as now provided by the applicable Code and Specifications), this diagram is still useful for checking the adequacy of the web itself, or the adequacy of a fillet welded web-to-flange joint, under certain special conditions of loading in some types of construction.

Fig. 16.—Maximum Combined (Principal) Stresses

Where increased area of web is required at one or two points, it is usual to butt weld additional plate to the tee stem.

Another form for this type of truss employs beam sections for chords and web members with webs of all members in the sections by fillet (or butt) welds. The chords of both types of trusses are well adapted to carrying concentrated loads between panel points, the beam type generally offering a greater resisting moment than the tee. A disadvantage of the beam truss

is that for certain proportions it is difficult to bring the lines of force to an intersection at the neutral axis of the chord member, which may introduce objectionable secondary stresses.

On the other hand it is now considered by some investigators that too much consideration has been given in the past to eccentric conditions of this character, at least for trusses carrying static loads. In this connection it has generally been considered necessary to arrange the welds at the ends of angle web members to balance the eccentricities produced by the location of the center of gravity of the angle section. Tests reported indicate the distribution of stress in the angle and the ultimate strength is rather independent of the disposition of the welds at the joint.

Where members are made up of component parts such as, for example, two angle members, the individual members must be joined together to assure their acting in unison. Not only is it imperative that each element of compression members have an individual ratio of slenderness somewhat less than that for the whole member, but even tension members should be tied to insure against injury in handling and to insure that the member has sufficient rigidity when subjected to sudden loads.

For longer spans and heavier loadings requiring larger sections, the form of construction is less standardized and greater ingenuity is required of the designer. Probably the commonest form for such trusses is the use of rolled wide flange shapes arranged with their webs perpendicular to the plane of the truss. Using members of the same nominal depth brings the flanges into two planes to facilitate the transmission of large stresses by direct welding. Preferably the joints should be butt welded directly, though some joints may require supplementary plate attachments.

The use of gusset plates in a double web system such as would be used in riveted trusses of this type is not efficient in welded construction since differences in actual depths require filler plates which greatly increases the welding cost, and often make a proper transfer of stress extremely difficult.

While many other variations in truss design have been developed, some of them very ingenious in the use of material, the cost of joint preparation often offsets other savings, resulting in higher overall cost. This is particularly true where excessive joint preparation is applied to the lighter types of trusses. One of the advantages of the tee-chord and angle-web truss, is that most members may be sheared with square cuts, to ordinary tolerances. (See Figs. 17 and 18 for typical truss details.)

Rigid and Semi-Rigid Frames

It is assumed in the design of rigid-frame tier buildings, that the joints are so rigid that virtually no deformation occurs within the joint, and that the angles between the various members around the joint remain essentially constant throughout any cycle of loadings. While this ideal condition is not possible of attainment employing elastic materials, it is nearest to achievement with properly designed welded details.

The most common form of joint employs plate connections on the top and bottom flanges of the beam, butt welded to the column and fillet welded to the beam for the full moment at the usual allowable unit stresses, making due allowance for wind stresses where such stresses are involved. The vertical forces are carried by a stiffener under the lower plate unless architectural requirements prevent, in which case web connections may be employed. (See Figs. 19 and 20 for typical rigid frame details.)

Assumptions that certain portions or groups of welds carry vertical loads while other portions of the same group carry moments are to be used with care. While such assumptions have been quite common to riveted construction particularly as applied to connections for simple beams upon which wind connections have been superimposed, and such details have apparently functioned satisfactorily, nevertheless the rigidity inherent in welded connections generally requires that the group of welds be considered as a unit under various combinations of applied forces. Where the time saved in design justifies the more conventional assumptions of distribution of forces and stresses and sufficient experience has been had with the behavior of the specific assembly such short cuts may be justified; but it should be recognized that the true maximum unit stress may be differently located and of a much larger amount than

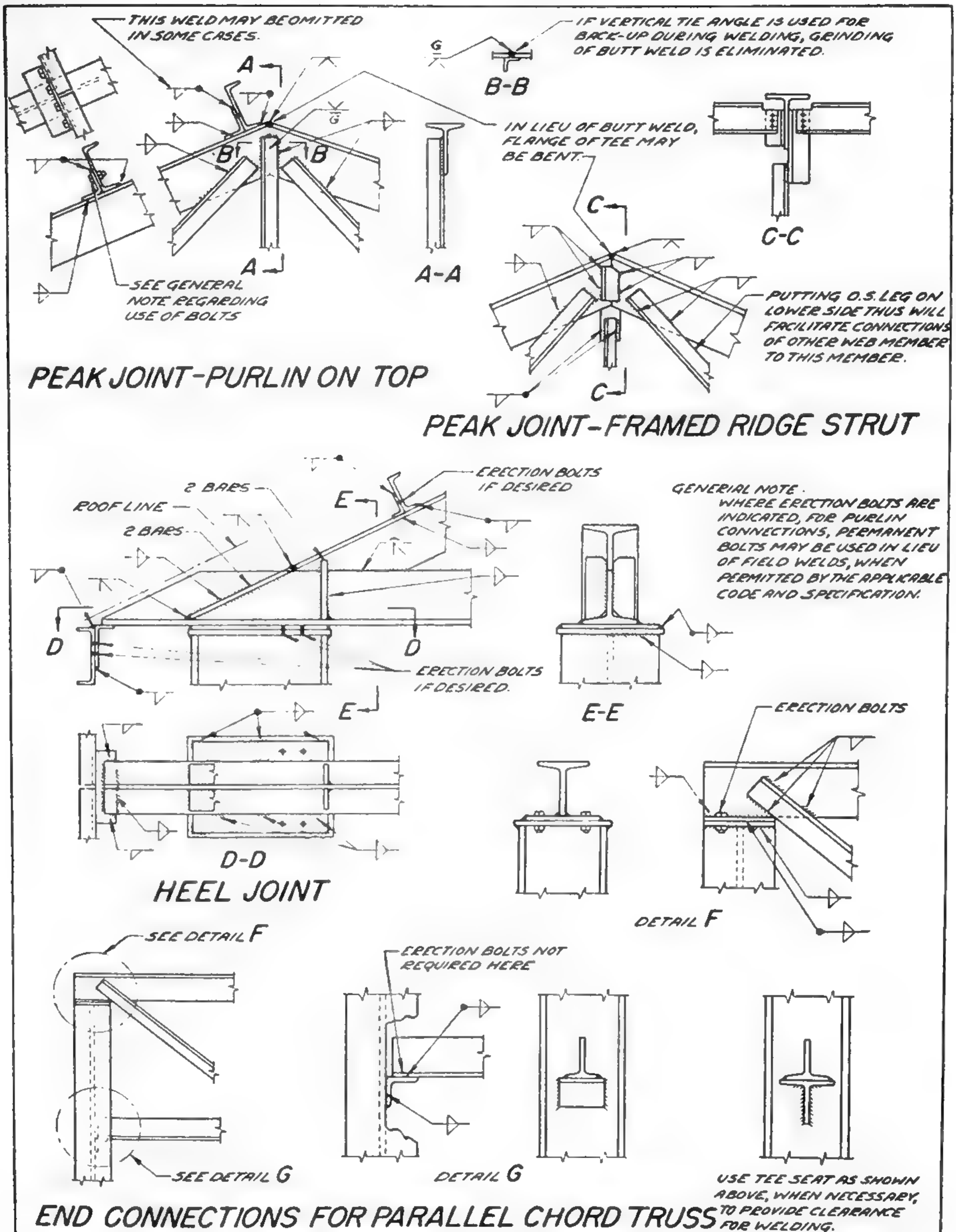


Fig. 17.—Typical Truss Details

that determined by the conventional analysis, unless the stress is limited in some manner by permanent deformations of some parts of the connection material, a phenomenon common to many types of joints.

The design of the joints of *semi-rigid frames* follows the same procedure as for rigid frames except for the degree of restraint which must be established by the results of tests of joints of the same type and general characteristics as those

used. In both rigid and semi-rigid joints the degree of restraint obtained for the joint depends not only on the disposition of the joint material and the size and location of the welds, but is also largely affected by the thickness of the webs and flanges of the sections connected as well as the use and distribution of stiffeners in the connected sections. The overall effective end-restraint of beams is influenced also by the flexibility of the supporting members.

Simple forms of rigid frame joints for one- and two-story industrial structures are illustrated in Figs. 19 and 20. The general arrangement and distribution of shop and field welds is clearly indicated. The determination of the stresses at the various sections of a rigid frame is covered in books on structural design. Since the allowable unit stresses in the butt welds preferred for these joints are equal in value to the corresponding unit stresses in the base metal of the component parts of the connected members, the design of the welds offers no difficulty. Care should be taken, however, to locate welds and splices so that the points of highest stress concentration occur as far as practicable in the base metal. Design utilizing these principles will result in a structure of such ductility and pliability that overstresses, due to inaccuracies of fabrication and erection, or from unusual loading conditions during or after completion, are relieved by plastic flow resulting in redistribution of stress; and a safe, efficient structure.

WORKMANSHIP

Tolerances

In the rolling of structural shapes, some variation from the theoretical dimensions is inevitable. While this fact is well known to fabricators, it is often overlooked by the designer, leading to increased cost of fabrication or erection.

The permitted variations from theoretical dimensions, commonly called *mill tolerances* are established by mutual agreement between the producers and users of structural shapes and plates, and may be found in any rolling mill handbook and in the AISC *Manual of Steel Construction.* Welded connections should be so designed as to anticipate variations up to the maximum permitted tolerance or a method for their compensation should be decided upon in advance. In many cases it is not feasible to match separate shipping pieces in the shop, and therefore the first knowledge of any variation is gained only after the parts are brought together during the field erection, when, for lack of the proper facilities, it is difficult to correct the variance, and additional cost and inferior workmanship may result. It should also be noted that such variations are often more apt to prove cumulative when several parts are involved, than they are apt to cancel one another.

There are also limitations to the fabrication tolerances which may be expected. In riveted construction lap joints were the usual thing and fabricators were used to assembling parts with the usual mill tolerances and the mill cutting tolerance which in most cases is of the order of ±3/8 inch. When shops accustomed to joints which can accommodate such variations are called upon to fabricate members which are to be assembled by butt welding, where the joint is to have a root opening of 1/8 in. with a +1/16 in. tolerance at each end, it is natural for the closer tolerance to result in greatly increased costs until the shop is organized to work to the closer tolerances required for such butt-welded joints. Many fabricators who gained considerable welding experience, fabricating subassemblies of ships during the late war, are now in a position to work to much closer tolerances, not only because they have installed more precise cutting equipment and learned more about the use of jigs and fixtures, but also because they have learned to predict the effect of welding upon the length and finished shape of a welded assembly.

Distortion

For the most part very little if any attention is required to prevent distortion from the heat of welding in structural work. However, the use of welding without proper control in the joining of some structural units into composite members may result in distortions which are costly to correct, but which are predictable to a certain degree and hence can be controlled or eliminated. There are several stages where care and knowledge may be applied to achieve the desired result. If the designer selects the parts of a com-

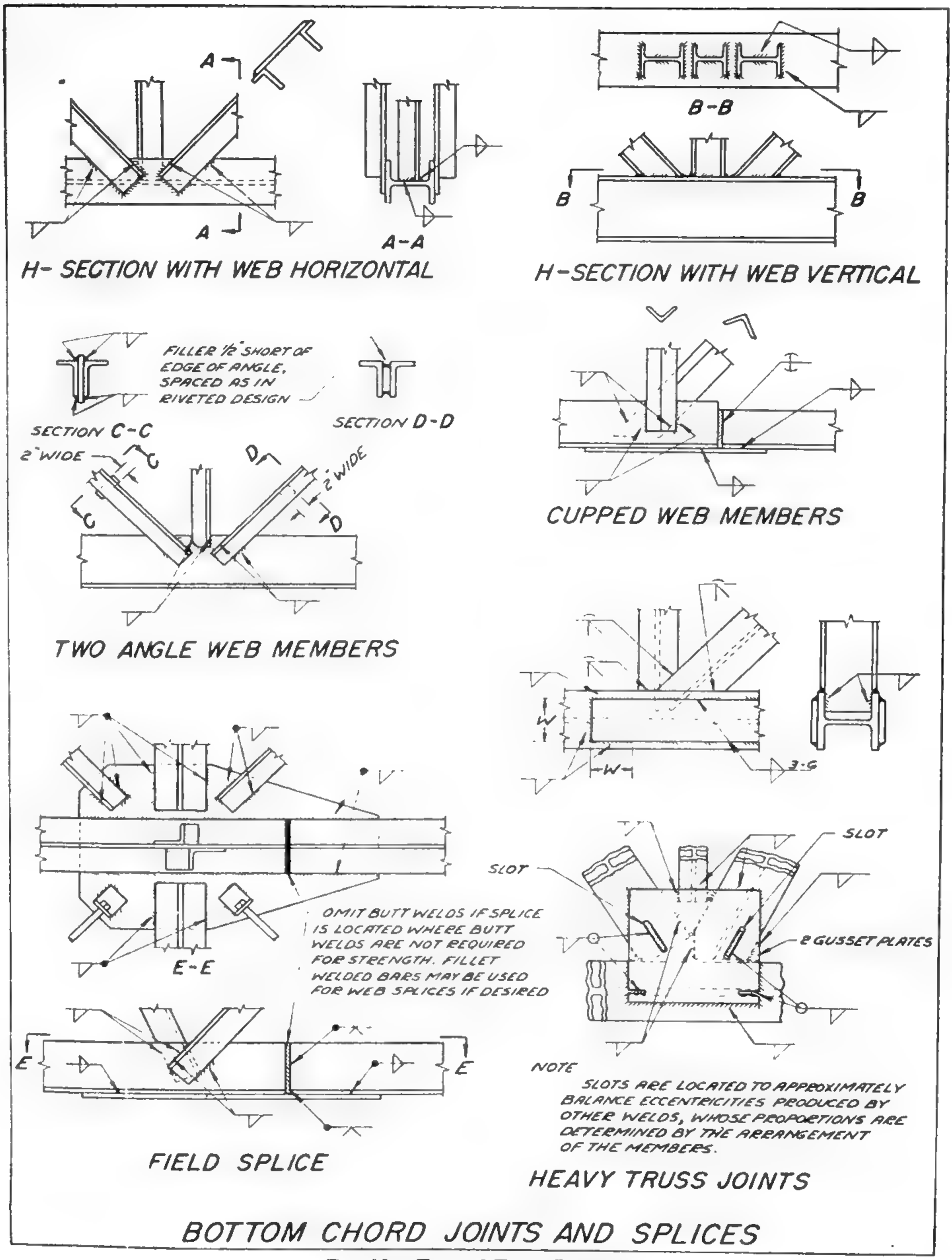


Fig. 18.—Typical Truss Details

posite member so that the amount of welding on each side of each axis is balanced, the detailer and the welder will have an easier problem.

The detailer should have experience and knowledge sufficient to detail the members and joints so as to reduce to a minimum the effect of unbalanced heated areas. Where the designer and detailer have done their work well, it is

only necessary for the welder to use a procedure which balances the application of heat to produce a final result which meets the desired tolerances. While it is possible for the shop to correct some of the shortcomings of the designer and the detailer, obviously the best results are obtained when all three are familiar with the problems involved and perform their part in the production of the finished product.

Many designers and detailers do not realize that when two or more elements are assembled into a composite member, distortions may result which require expensive shop straightening before shipment. When this is coupled with the present tendency in architectural practice to require exposed structural members at the sides and eaves of industrial buildings, to provide almost perfect alignment for continuous steel sash, glass block construction and finished eave lines, this straightening process may be an important cost item.

For example, where an angle is riveted to the flange of a channel, the punching of holes in the channel tends to increase the length of the outer edges of the flange with respect to the back of the channel producing a bow in the channel. Subsequent riveting may accentuate this effect. Attaching a masonry plate or combinations of plate and angle to a beam has the same effect where there is a much larger number of punched holes on one side of the center line. The effect of welding in place of riveting such assemblies is to produce similar camber in the opposite direction. Riveted buildings, ships, etc., tend to grow and result in greater length than the sum of the units, while welded structures tend to shrink, resulting in a shorter finished structure, unless allowances are made for the effect on the structure of the joint construction employed.

The explanation for the shrinkage due to welding depends on the particular welds involved. Where isolated spots are heated by welding to a fluid or plastic condition the restraining action of the surrounding cold metal forces the resulting increase in volume to occur in the unrestrained direction. Solidifying in that state while cooling locks in the upset and while the original volume is regained the increased thickness due to the upset reduces the area and results in a residual tension which must be balanced by an area of residual compression, resulting in a reduction in the length of the member. The application of heat in this manner may be employed to take out buckles in plates or to straighten a curved structural member. A somewhat similar effect is obtained when a longitudinal weld is employed. The shrinkage of the weld metal results in a residual tension in the weld, balanced by areas of residual compression in the surrounding base metal and a reduction in length or local buckling. If the weld is on one side only of the neutral axis a curved member results. When fully aware of the effects of welding, the designer may arrange the parts of a composite member to eliminate or greatly relieve this condition. For example, where a masonry plate is attached to a beam to carry masonry on one side only of the center line of the beam, increasing the width of plate so that the connecting welds may be made on both edges of the flange will aid in balancing the welds and reducing the distortion.

Where equal amounts of welding are not possible on both sides of the center line there are several other effects which, if controlled, will assist in producing the desired result. Since continuous welds result in greater shrinkage than intermittent welds, varying the lengths and sizes of the welds to offset varying distances from the neutral axis may assist in balancing the shrinkages. Another phenomenon which may be utilized to advantage is that where equal welds are placed on opposite sides of the center line and one of these welds is completed before the other is started, the distortion effect of the second weld never quite equals that of the first weld. Even where the welds are balanced, distortion from this effect may result. This is best controlled by welding the two welds simultaneously, employing two qualified welders, though it may also be accomplished by alternately welding short lengths on each side in a wandering sequence.

Another cause of excessive distortion is the tendency of some designers, unfamiliar with welding, to use an excess of welding. It is hard for them to conceive of the great strength possessed by small welds, so they design by *feel* or *appearance* rather than by comply-

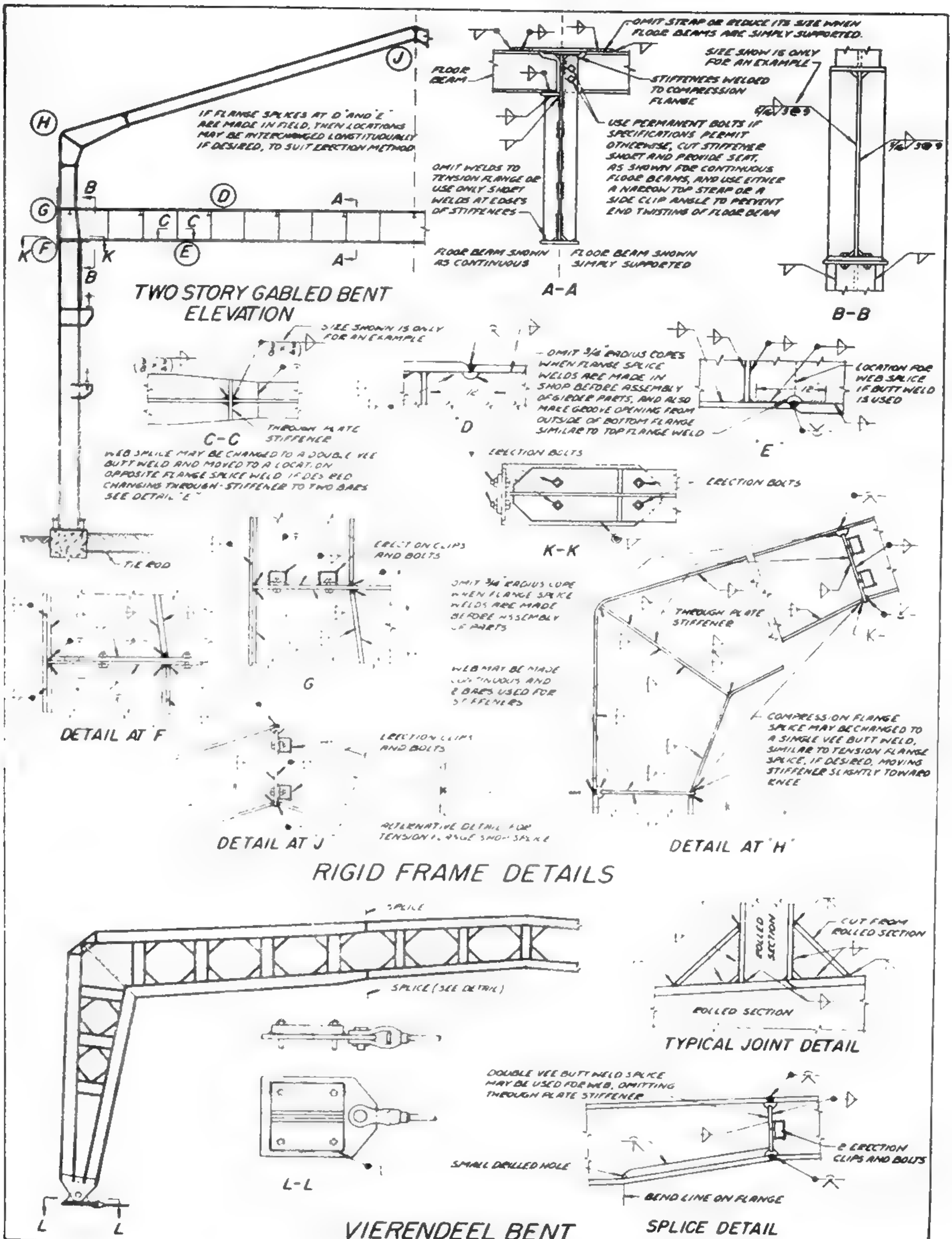


Fig. 19.—Typical Rigid-Frame Details

ing with the Code. Such overwelding adds greatly to the cost, exaggerates the distortion problem and requires more drastic straightening operations.

It is also possible for the excess heat input resulting from overwelding to raise the temperature of the base metal at some points sufficiently to reduce the ability of the material to resist residual stress introduced in the steel mill during the operations of rolling, cooling, cold straightening, etc., with the result that

distortion occurs. Since the existence and location of such residual stress is impossible to predict, the distortion produced by the excessive application of welding is unpredictable.

Where the designer is familiar with the problems of welded design, the distortions which may result and how they may be overcome in design and detail, it is desirable to show on the design drawings the results of this experience. Where this knowledge is not possessed by the designer it would be preferable for the designer to outline the main considerations only, and leave to the fabricator the detailing and fabrication, first having assured himself of the competency of the fabricator.

Shop organizations learn by experience how to overcome the problems of distortion during fabrication. Since variation in the procedure can result in comlete reversal of distortion under some conditions, and the degree and direction of distortion can only be anticipated after considerable experience with the same or similar assemblies, the amount of experience and general ability of the shop organization will be reflected in the fit and straightness of the finished structure and to a degree will also be reflected in fabrication costs.

Painting

It has generally been considered poor practice to permit welding through paint, whether a new coat of shop paint or several coats of old paint such as would be encountered when repairing or altering existing structures. Some specifications require that all paint be omitted or removed within two inches of the weld, although a coat of linseed or other light oil without pigment is generally considered to be acceptable. Other specifications permit the use of a comparatively thin primer coat of certain kinds of paint.

The practice of using a linseed oil shop coat has never been considered to be a good solution; in fact, the results obtained hardly justify the cost of application, since the thin oil coat becomes very badly abraded in the course of handling during shipping and erection. It has none of the self healing properties of a good paint coat, does not dry hard and altogether affords rather poor protection against corrosion even for temporary service. Furthermore, it is doubtful if it is any easier to weld through a coat of linseed oil than it would be to weld through a thin coat of iron oxide or zinc chromate primer.

The alternative of applying a good coat of shop paint, with paint omitted at the field welds, generally referred to as striping, is not very satisfactory either, for it increases appreciably the cost of applying the shop coat, and it increases the cost of the field touch-up coat. In fact, it is really only practicable when there are large enough areas free of field welding so that the total cost of shop painting with areas to be field welded omitted, plus the cost of touch up, is less than the cost of application of the first coat in the field.

The fabrication industry has never taken too kindly to the use of a linseed oil shop coat, nor to the extra expense involved in striping. Nor is the alternative of omitting the shop coat and painting two field coats much more acceptable. On the other hand, many experienced welding operators have maintained that, given a bare spot on which to start the arc, they could produce acceptable welds on new or old paint. Some structures have been built or repaired under such conditions with apparently satisfactory results.

The most recent report on this subject indicates that the presence of paint on the joint before welding has little effect upon the strength of the finished weld, but that such films present an obstacle to the production of the weld, and affects the appearance of the weld, varying with the experience of the welder with welding through paint and with the thickness of the paint film.

It was found that iron-oxides had practically no effect on the welding, while zinc-chromate, graphitic-mica, zinc-oxide, titanium dioxides and magnesium-silicate had only a slight effect on the external appearance and soundness of fillet welds. Lead sulfates (blue lead, white lead, basic lead sulfates) produced arc instability and poor appearing, porous welds. A 98% red-lead pigment showed definitely deleterious effect, while red lead slurries exceeding 75% red-lead resulted in poor appearance and porous welds. A 25% iron oxide, 75% red lead produced acceptable results, which improved as the red-lead percentage was decreased and the iron oxide increased.

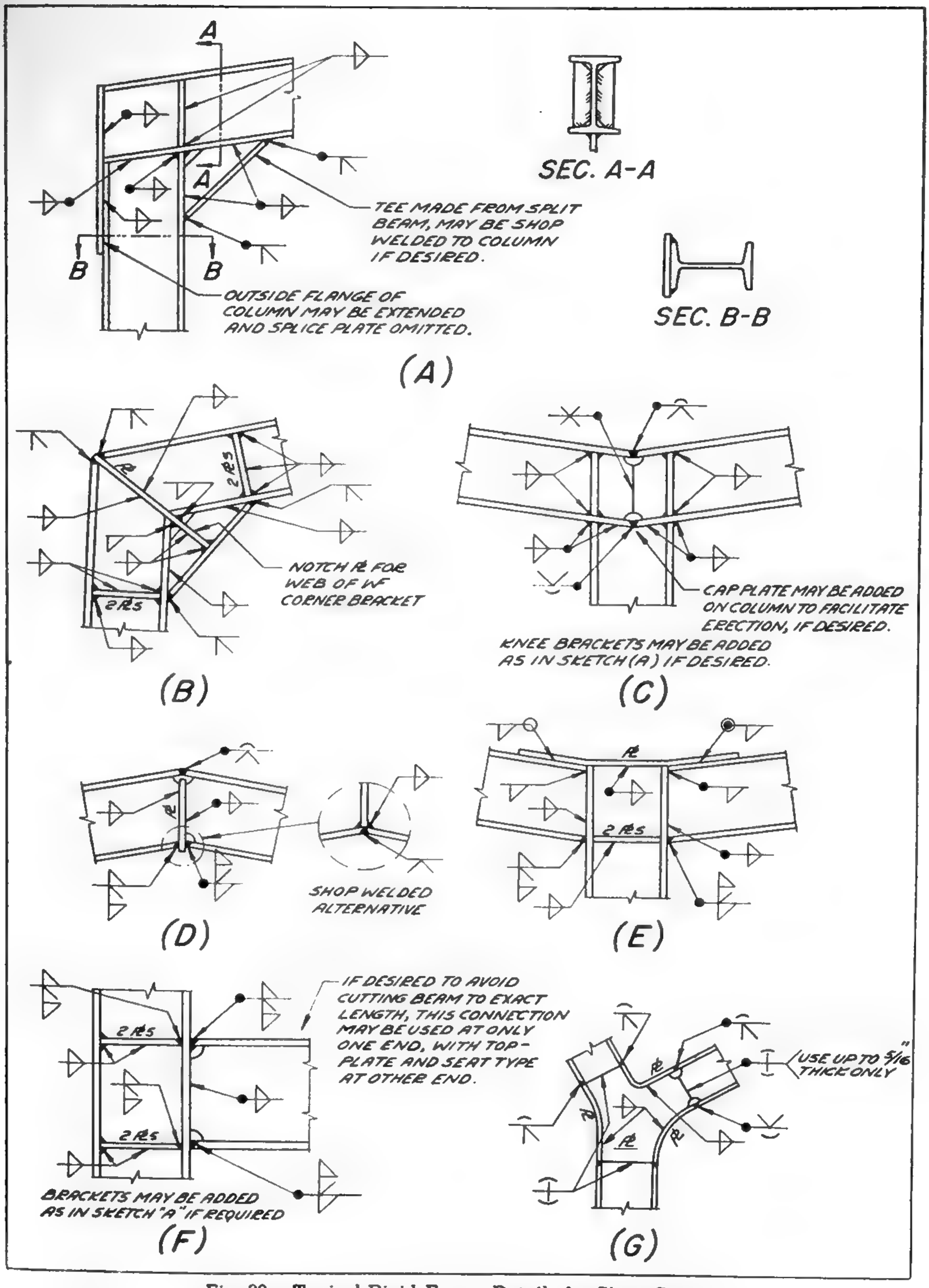


Fig. 20.—Typical Rigid-Frame Details for Short Spans

Welds made through unpigmented vehicles showed no bad effect even in thicknesses of dry paint coats exceeding the 1 to 3 mils (0.001 to 0.003 in.) which was found to be the satisfactory range of thicknesses for acceptable pigmented

paints. Coats thicker than 3 mils generally caused some difficulty, particularly on vertical welds, apparently because of the lower welding currents used.

In multiple-pass welds difficulty was encountered on the first pass only, since the adjoining paint was generally so burned in making the first pass that it was either removed completely or was so charred that the wire brushing between passes removed it entirely.

The recommended practice based on this report would be to use a thin shop coat, not to exceed three mils in thickness, preferably of an iron oxide or zinc chromate paint. After field welding through this paint, the slag should be thoroughly cleaned and the burned areas touched up with the same paint as the shop coat, after which the field coat may be applied.

For those structures where exposure to weather or corrosive gases would require more protection than would be obtained from the above paint procedure, rather than apply a third coat, it may be more desirable to omit the shop coat entirely, applying two heavy field coats. This would certainly be better where the steel would not be exposed to any considerable corrosion between fabrication and erection. For those cases where unusual exposure between fabrication and erection may be expected, the three-coat procedure would be indicated.

The practice of painting contact surfaces before assembly either in the shop or in the field is to be avoided for either welded or riveted construction. While specified in older specifications, more recent tests and experience indicate that this practice does not improve the joint, may actually reduce the strength in a riveted joint, increases the cost, and constitutes a health hazard for either riveters or welders. Local safety regulations should be taken into consideration in connection with flame cutting or welding on painted surfaces. (See Chapter 46.)

Erection

Erection of welded construction should be at least as efficient as for riveted construction. The welders can quite generally follow more closely behind the setting gang, their progress being limited only by the plumbing-up of the steel frame. Another factor is the greater ease of movement of the welder from one point to another, since, generally, no scaffolding is required, no heater, bucker up, rivet catcher, etc.; one man replacing the whole rivet gang. Efficiently organized, field welding is generally less costly than field riveting.

While clamps, clamping devices and jigs are used rather extensively on some classes of shop welding to hold the parts in line, or in contact, they are not in general use in the field welding of framed structures, even though the use of clamps and hitches of various sorts is quite common to plate and tank work, and in ship work, where the lining up of contiguous parts of large plate justifies such equipment.

The more usual practice in framed structures is to use ordinary rough bolts in punched holes to hold the members during plumbing and welding. Generally two bolts are used so arranged that the erection loads and the service loads are carried on shop welded seats, as far as practicable. Where erection loads are carried directly by the bolts, it may be necessary to increase the number. It is considered most economical to locate field bolts generally so that as far as possible holes are restricted to detail material. Since holes may be pierced with an oxygen-cutting torch at any stage of shop fabrication, thereby reducing the handling charges, it has become accepted practice to permit the use of flame-pierced holes for erection bolts. The employment of this device obviates the necessity for going to extremes to avoid holes in main material, which often results in awkward joints and increased welding.

The use of a minimum of two bolts is desirable even for minor bracing, since the connector can pin through one hole with the spud end of his wrench, prying the holes into line, until he can place a bolt in the second hole. Depending on the location and importance of the joint, a second bolt is then placed in the other hole and both bolts turned up tight, or a drift pin is placed in the second hole and driven up tight, although in some cases the second hole is left open. In any case, after the completion of the field welding, the erection bolts are usually permitted to remain in place, since the cost of removal usually exceeds the value of the bolts, though drift pins are removed since it takes but one or two sharp raps of a hammer to remove them.

For some forms of rigid frame where

the joints are left exposed and a more pleasing appearance results from smooth areas, clear of all bolts and nuts, the use of welded hitch plates or angles is common with all the holes in the hitch material, which is flushed off with the oxy-acetylene torch when the welding has proceeded to a point where the hitch is no longer required. The surface is then chipped or ground flush before painting.

In an otherwise all-welded structure it is considered good practice to use rough bolted connections, where specifications permit, for such items as roof purlins, roof bracing, girts and secondary beams. Since two bolts would generally be required for erection purposes alone, and few or no additional bolts to carry the service load, it should be obvious that substantial savings result if the joint is designed for field bolting.

For a series of bents, particularly rigid-frame bents with rather large knee and ridge joints, some erectors prefer to do the welding on the ground and raise the bent into position in one piece. This practice is limited by the relative size and weight of bent and the available hoisting equipment (and the personal preference of the erector) and it is advisable to determine whether the joints are to be welded on the ground or in the air before designing the details of the various joints. It is recommended that procedures be set up for erection and welding sequences to facilitate erection, control distortion, and assure preferred stress distribution in members and connections.

For some types of structures the accuracy in fabrication is not much different from what would be required for riveted construction. This would be true of simple beam and column construction where the gravity loads are carried on shop-welded seats with two bolts to hold the beam during plumbing; loose top angles or top plates are field welded in position, and the beams are cut to usual mill-cutting tolerances. However, if erection costs are not to be greatly increased the fabrication must be much more carefully done and to much closer tolerances for structures employing butt-joints. Where the abutting edges of joints are too close to permit penetration at the root, expensive field cutting or chipping must be resorted to; if the root opening is too wide the volume of welding is greatly increased. In excessive cases, backing plates or extension pieces may have to be used.

It is often possible when designing rigid frames to arrange the locations of the field splices so they occur in the narrower portions of the rafter beam, preferably at or near the point of inflection so that the field welding is reduced to a minimum, and the highly stressed knee joint may be completely shop welded where the control of joint clearances and the welding of the more highly stressed joints may be much more efficiently accomplished.

Unlike riveted connections where open holes are an unmistakable indication of the location of bolts or rivets it is necessary in welded construction to furnish adequate erection sketches indicating the size, type, location and sometimes the sequence for placing the required welds. Under certain ideal conditions such as the standardized connections referred to elsewhere in this chapter, the field welding has been so standardized that the pattern is soon memorized and only a few typical notes or sketches on the erection drawing are sufficient; whereas, if a considerable number of special details are used, drawings must be furnished showing complete details of the various joints, using identifying symbols on the erection drawing and the sketches. These sketches should preferably be made on forms small enough to be bound into sets which may be carried in the workman's pocket.

It is considered good practice to have a welding supervisor, foreman or assistant engineer locate all welds on the steel from the sketches furnished, indicating sizes and lengths of all welds, using lumber crayon or paint, so that the marks will remain until painted out. This permits the welder to concentrate on the welding operation, resulting in cheaper and better welds. After the welding is completed at the joint, the inspector can then check the work against the marking on the steel, also comparing the work with his copy of the detail sketch, thus eliminating the possibility of omitting any of the field welds.

INSPECTION

In any kind of fabrication or construction work, the work of inspection is made easy or more difficult, depending upon the amount and adequacy of the direct

supervision imposed upon the production forces. One of the principal duties of an engineering-inspector is to see that competent and sufficient supervision is provided, taking care however, not to interfere with those phases of control which are properly the responsibility of management.

Although the lack of a practical, generally applicable, non-destructive test for completed welds has been deplored by some structural engineers, no comparable tests have been developed, nor deemed desirable, for other forms of fabrication. The most effective way to insure good quality of workmanship, and sound construction, is to establish the essentials of the construction procedure to be used, and then to exercise sufficient inspection over the work during its progress to assure that the essential requirements are being met.

The workmanship clauses of the American Welding Society's Code, and the American Institute of Steel Construction's Specification, referred to throughout this chapter, establish the essentials of prequalified welding procedures which experience and research have shown desirable. When procedures are proposed which do not conform to those which have been so prequalified, the process for obtaining approval of such procedures is also described in the Code and Specification conforming to the requirements of the American Welding Society's *Standard Qualification Procedure*. The same documents describe the procedure for qualification of welding operators.

While a number of methods have been developed for spot checking welds, such as trepanning, radiographic examination, magnetic powder testing, etc., they require comparatively expensive operations, which are seldom necessary for ordinary welded structures. It is generally considered that adequate assurance of weld quality can be obtained, where an experienced inspector is present while the work is performed, actually observing the welding operation at intervals, so that the welder knows he is under the direct observation of an experienced person who knows what to look for; one who can tell by surface appearance of single-pass fillet welds whether proper current was used; whether the technique used and weaving, if any, is such as to assure adequate root penetration, and similar conclusions which may be drawn from visual inspection.

For a complete description of the duties of the inspector, the American Welding Society has published the *Inspection Handbook for Manual Metal-Arc Welding*. In brief, the inspector should assure himself that the specified electrodes are used, that the currents used are in accord with the manufacturers recommendations, and suitable for the position of welding; that the joints are prequalified or have been otherwise qualified in accord with AWS procedures; that the welder has passed the required qualification tests for the work he will be called upon to perform; that the welds are made in accordance with the established procedures; and the material preparation and fitting-up conform with accepted standards and specifications. After the welding is completed he should assure himself that all of the welds called for on the drawings have been actually made, that they are accurately located and of the specified sizes. He should also check the finished welds for size, length and standards of workmanship with respect to contour and appearance of the weld surface, surface defects, craters, undercutting, overlapping edges of welds, cracks, etc.

Both shop and field inspectors should employ check methods which automatically prevent omission of welds. This may be accomplished by having the welding supervisor mark on the work with materials which will not be erased during handling, the size, length and location of all welds. After completion of the work, the inspector can check these markings against the work performed and also against his own set of drawings and eliminate the possibility of omissions and wrongly located welds. Weld location is important; placing welds in the wrong location may be just as serious as omitting the welds altogether, since excessive stress may be developed in a wrongly located weld at a joint which has been designed to flex or yield plastically with properly located welds. Over-welding either in size or length of welds is to be discouraged, for such practices not only increase welding costs, but may also introduce distortions, the correction of which may be both costly and difficult.

ESTIMATING COSTS

Any comparison of the relative costs of welded construction with other methods of joining should take into consideration such intangibles as appearance of the finished structure, together with lower maintenance costs of exposed steel; decreased weight of moving elements such as cranes, resulting in lower operating costs; greater ease of access for alterations or additions; as well as any saving which may be obtained in first cost of the structure.

The saving in steel cost will vary with the type of structure, the skill of the designer in utilizing the inherent advantages of welding; the experience of the fabricator in planning and organizing the work, and in the employment of jigs and fixtures; the use of welding procedures and sequences to control distortion and to eliminate expensive straightening operations; and with the skill and experience of the erector.

Weight savings have been obtained as high as 20 to 25% for rigid frame construction of large mill buildings, auditoriums, hangars, etc; 10 to 15% for mill buildings with roof trusses; 15 to 30% for industrial handling equipment; while for conventional tier buildings the reduction in weight has been as low as 5 to 10%. Certain elements of such structures may show savings in weight as great as 20 to 30% for truss type mill building bents, 20 to 35% for built up plate girders, and 15 to 30% for welded trusses.

Where the factors of skilful design, economical fabrication, and experienced erection are all favorable there should be a reduction in the various unit costs which will substantially increase the total savings. However, a design prepared without proper consideration for fabricating and erection costs can result in increased unit costs which will offset most if not all of the savings accomplished by reduction in the weight of material. The use of standardized details, wherever they are appropriate, results in a saving in detailing and fabrication costs as well as reducing the cost of preparing the design. Such a system of standardized details is described in the paragraph on the design of joints.

In order to accurately estimate costs of welded construction it is essential that the estimator be experienced in the various factors which enter into the cost of such structures, just as an estimator of any form of structure must have a knowledge of costs, which can only be acquired through experience. Experienced estimators of welded fabrication find that costs can be estimated just as accurately as can those of other items of construction. The labor item, of course, varies with local conditions as it does in any kind of construction. (Chapter 41 contains data for estimating welding costs.)

Only by acquiring sufficient skill and experience in welded construction to properly evaluate all the variables can an engineer know what economies are possible in any specific case. Even the common device of taking alternative bids may not be conclusive, since the bids may merely reflect a transitory market condition. Obviously, a steel fabricator whose shop organization and procedures are set up for riveted fabrication is unlikely to quote a lower price for a welding alternative in a seller's market. The same alternatives submitted in a buyer's market, or quoted by a fabricator whose shop is organized for welded fabrication, will be more likely to reflect the relative costs of the two designs.

While conditions may make it difficult at times to obtain theoretical price advantages in borderline structures, such as simple beam and column construction; where such structures must be designed to resist lateral forces, such as wind pressure, the necessity for stiffer joints, introduces factors more favorable to welded construction. Depending on the size of building and the magnitude of the lateral forces, the structural frame may be designed as a rigid frame, semi-rigid frame, or the top plate wind-bracing connection may be employed as described on page 1094.

Welded fabrication, like most technological improvements, has met with considerable resistance, except for those applications where some overwhelming advantage overcomes this resistance. This has been true of certain welded plate work, such as oil storage tanks and similar structures, where the maintenance costs of riveted structures are excessive due to the necessity for repeated caulking. When such savings are added to the

saving in first cost, owner demand overcomes all objections. This is true also, in those cases where customer demand for greater aisle width and elimination of unsightly trusses and shadows has resulted in the adoption of rigid frames for it is in such structures that welding offers the greatest advantages and economy.

BIBLIOGRAPHY

1. *Investigation of Web Buckling in Steel Beams,* Inge Lyse and H. J. Godfrey, ASCE Proceedings, February 1934 and November 1934.

2. *Fillet Welds Subject to Bending Stresses,* Norman G. Schreiner, The Welding Journal, September 1935.

3. *Stress Distribution in Welds Subject to Bending,* C. D. Jensen and R. E. Crispen, The Welding Journal, October 1938.

4. *A Photoelastic Study of Bending in Welded Seat Angle Connections,* Inge Lyse and D. M. Stwart, The Welding Journal, February 1935.

5. *An Investigation of Welded Seat Angle Connections,* Inge Lyse and Norman G. Schreiner, The Welding Journal, February 1935.

6. *Oxyacetylene Welding and Cutting Welded Structural Brackets,* C. D. Jensen, The Welding Journal, October 1936.

7. *Flexible Welded Angle Connections,* Bruce Johnson and Lloyd Green, The Welding Journal, October 1940.

8. *Tests of Miscellaneous Welded Building Connections,* Bruce Johnson and Gordon R. Deits, The Welding Journal, January 1942.

9. *Report of Tests of Welded Top-Plate and Seat Connections,* J. L. Brandes and R. M. Mains, The Welding Journal, March 1944.

10. *Advantages of Welding in Continuous Structures,* Inge Lyse, The Welding Journal, February 1936.

11. *Welded Beam Column Connections,* Inge Lyse and Glenn J. Gibson, The Welding Journal, October 1936.

12. *Effect of Welded Top Angles on Beam Column Connections,* Inge Lyse and Glenn J. Gibson, The Welding Journal, October 1937.

13. *Effect of Rigid Beam Column Connections on Column Stresses,* Inge Lyse and E. H. Mount, The Welding Journal, October 1938.

14. *Designing Welded Frames for Continuity,* Bruce Johnston and E. H. Mount, The Welding Journal, October 1939.

15. *Economical Design Through Restraint in Beam Connections,* Bruce Johnston and Robert Hechtman, Engineering News-Record, October 10, 1940.

16. *Analysis of Building Frames with Semi-Rigid Connections,* Bruce Johnston and E. H. Mount, ASCE Proceedings, March 1941.

17. *The Practical Design of Welded Steel Structures,* H. M. Priest, American Welding Society, 1943.

18. *Arc Welded Steel Frame Structures,* Gilbert D. Fish, McGraw-Hill Book Co., 1933.

19. *Design of Welded Buildings,* Gilbert D. Fish, American Welding Society Welding Handbook, 1938.

20. *The Design of Welded Seat Angle Connections—Flexible Type,* Heath Lawson, The Welding Journal, June 1935.

21. *Standard Details for Welded Building Construction,* Heath Lawson, The Welding Journal, October 1944.

22. *Manual of Design for Arc Welded Steel Structures,* LaMotte Grover, Air Reduction Sales Company, 1946.

23. *An Investigation of Welded Connections for Angle Tension Members,* Glenn J. Gibson and B. T. Wake, The Welding Journal, January 1942.

24. *Studies on the Effects of Red Lead Paints on the Quality of Metal Arc Welds in Structural Steel,* R. W. Bennett, R. D. Williams and C. B. Voldrich, The Welding Journal, November 1947.

25. *Specifications for the Design, Fabrication and Erection of Structural Steel for Buildings,* American Institute of Steel Construction, 1946.

26. *Standard Code for Arc and Gas Welding in Building Construction,* American Welding Society, 1946.

CHAPTER 48

BRIDGES*

GOVERNING CODES AND SPECIFICATIONS

THE DESIGN AND fabrication of bridges by welding is most often done in accordance with the AWS *Standard Specifications for Welded Highway and Railway Bridges.* These Specifications are, however, intended to be used in conjunction with the governing basic specifications.

In general, railway bridges are designed in accordance with the specifications of the American Railway Engineering Association and highway bridges are designed in accordance with those of the American Association of State Highway Officials. An analysis of the basic requirements of the fourth edition of the AWS *Standard Specifications for Welded Highway and Railway Bridges* is given in the following paragraphs.

The Specifications for any contract for an all-welded steel bridge should contain the following information:

Description of work contemplated.
Method of measurement (if on the pound price basis).
Basis of payment (whether on pound price or lump sum basis).
If on the unit price basis, how fillets are paid for.

MATERIALS

The AWS *Standard Specifications for Welded Highway and Railway Bridges,* like the general bridge specifications of the American Railway Engineering Association and American Association of State Highway Officials, contemplate that the steel used in new bridges, or in repairs to old bridges of steel, shall have a minimum yield point of 33,000 psi. and a minimum tensile strength of 60,000 psi. There being no standard specification available which will guarantee these minimum mechanical properties and will at the same time guarantee chemical and other properties ensuring weldability (except at considerably higher price), the following alternative provisions are made:

1. Steel not over 1-in. thick should conform to ASTM *Standard Specifications for Steel for Bridges and Buildings* (Serial Designation: A7) which guarantees minimum mechanical properties and which has been found by years of experience with commercial deliveries to seldom contain over 0.25% carbon in thickness up to 1 inch.

2. Steel from 1-in. to $2^1/_2$-in. thick should conform to ASTM Specification A7 to guarantee the mechanical properties and should be further investigated or treated in either of the following ways:

(*a*) A check test may be made on drilling and, if the carbon content plus one-sixth the manganese content does not exceed 0.40%, the steel is satisfactory for use with special precautions, or

(*b*) If no such check test is made, or if the carbon plus one-sixth of the manganese content is found by check test to exceed 0.40%, preheat and possibly postheat are to be employed.

3. In lieu of 2(*a*) and 2(*b*) the steel may be purchased to Federal Specification QQ-S-741, Grade A (Bridges), Type II (Welding Quality); which specifies the same minimum mechanical properties as ASTM A7 and also imposes a chemistry maximum of 0.31% carbon and 0.75% manganese and is sold by the mills under a substantial *quality extra.*

No specification is provided for steel over $2^1/_2$-in. thick, as its use is not covered by the AWS Bridge Specifications.

Low-alloy structural steel (ASTM A242), having a 50,000 psi. minimum

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* Prepared by a committee consisting of J. F. Willis, State Highway Dept., State of Connecticut, *Chairman;* F. H. Frankland, Consulting Engineer; LaMotte Grover, Air Reduction Sales Co.; Jonathan Jones, Bethlehem Steel Co.

yield point, is satisfactory for welded bridges but despite the higher unit stresses permissible, its cost makes its economic use in ordinary bridge structures a matter for careful estimating.

The foregoing carbon and low-alloy steels may all be welded using any of the electrodes in the AWS-ASTM E60 series of classifications. (See Chapter 38.)

Steel conforming to ASTM *Standard Specifications for Structural Silicon Steel* (Serial Designation: A94) is unsuited for welded bridges.

Where wrought iron base metal is to be used in the repair or strengthening of an existing wrought iron bridge, or where it is used for special corrosion-resisting purposes, as for base and cover plates, it should conform to ASTM *Standard Specifications for Rolled Wrought-Iron Shapes and Bars* (Serial Designation: A207) or *Standard Specifications for Wrought-Iron Plates* (Serial Designation: A42). Here again all of the electrodes in the E60 series of classifications are suitable.

DESIGN

Loads and Forces

The AWS Bridge Specifications contemplate that the loads and forces, the unit stresses on base material, the general requirements as to arrangement of parts, clearances, camber, etc., will be found in an applicable standard specification, such as that of AREA for railway bridges and that of AASHO for highway bridges; the only exceptions being those matters which are affected by the choice of welding as the method of construction.

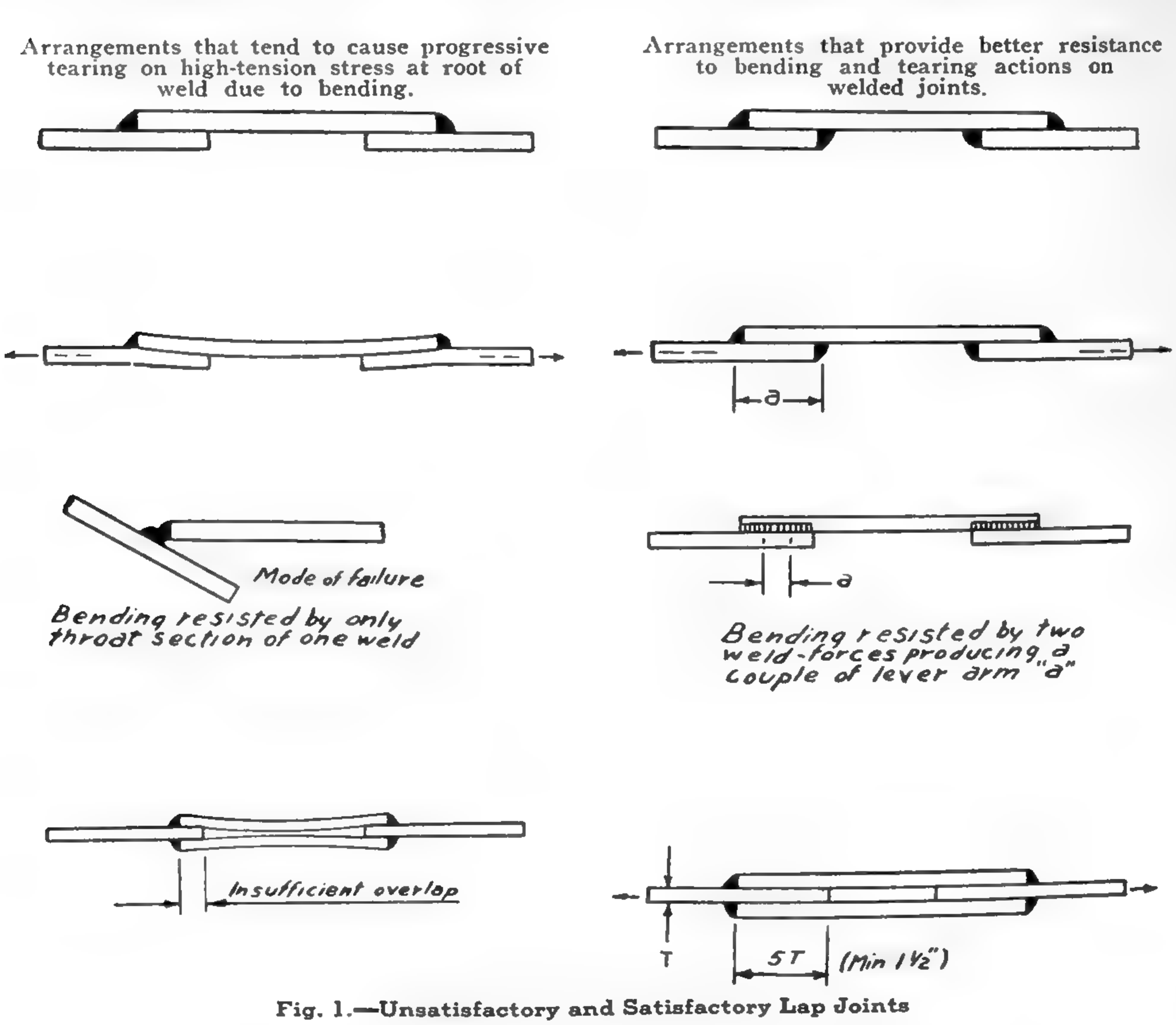


Fig. 1.—Unsatisfactory and Satisfactory Lap Joints

Type of Joint

The junction point or edges of any two or more pieces of metal to be united by welding is known as a joint. Therefore,

the predominant application of welding concerns the matter of joints.

Permissible Welds.—The AWS Bridge Specifications sanction butt, fillet, plug and slot welds provided they are in conformity with the standardized requirements set up. In this case no qualification of procedure is required. Unortho-

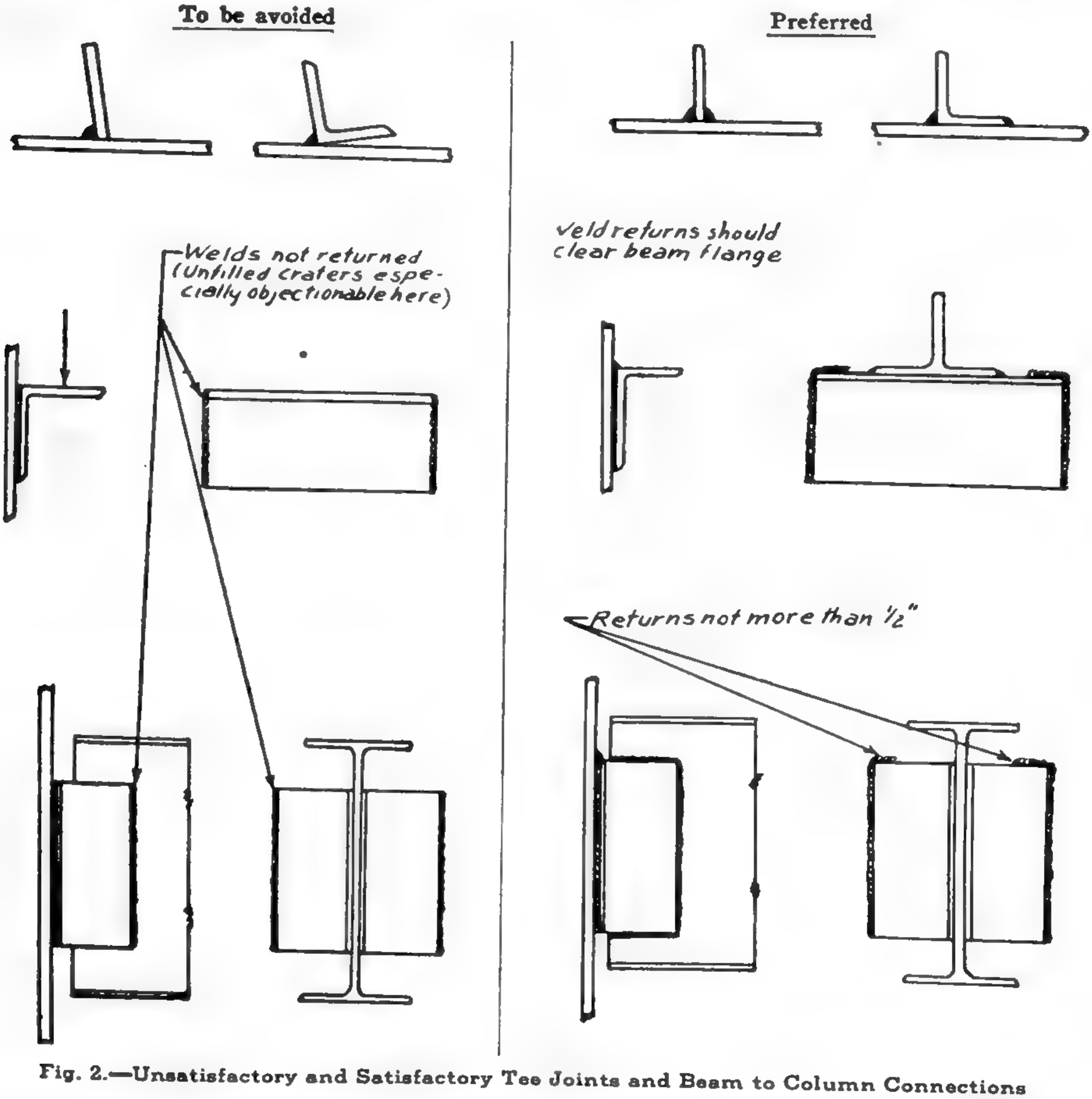


Fig. 2.—Unsatisfactory and Satisfactory Tee Joints and Beam to Column Connections

dox or non-standard joints are not ruled out if such can be proved adequate and suitable by the stipulated qualification tests.

Non-Permissible Welds.—The Specifications forbid the use of saddle welds (except for sealing), of intermittent butt welds and of butt welds made from one side only without backing.

Prequalified Joints.—In the category of prequalified joints are included butt welds, single- and double-vee, bevel, J and U grooves; also square edge material not exceeding $^1/_4$ in. in thickness. Prequalified details thereof embrace limits of maximum plate thickness and minimum included angles, root face, root opening, root radius contour and reinforcement. Alternative procedures are approved for transition butt welds between parts of unequal thickness.

Types of Welds

Butt Welds vs. Fillet Welds.—All research pertaining to joints has revealed the superiority of butt welds over fillet welds where fatigue is a consideration. As a consequence, fillet welds have been

penalized to an extent sufficient to encourage the use of butt welds wherever there is a possible choice of use. Obviously the stress lines have a much smoother path in the butt weld. Present test results on fatigue of butt welds are more consistent and dependable than those on fillet welds. There has been a tendency on the part of detailers, particularly those converts who follow riveting practices, to use the fillet-welded lap joint rather than the butt joint. Bridge specifications should place particular emphasis on the desirability of the butt weld.

Great stress is laid on the preference for continuous rather than intermittent fillet welding, out of consideration for fatigue strength as well as resistance to corrosion. The economy of intermittent fillet welding is often doubtful and never very appreciable.

Plug and Slot Welds.—These types of welds are permitted to carry calculated shear only and at the unit values for fillet welds in shear. The holes or slots may be filled by a continuous welding operation. The width of slot or diameter of hole should not exceed $2\frac{1}{4}$ times the thickness of the plate if of the filled

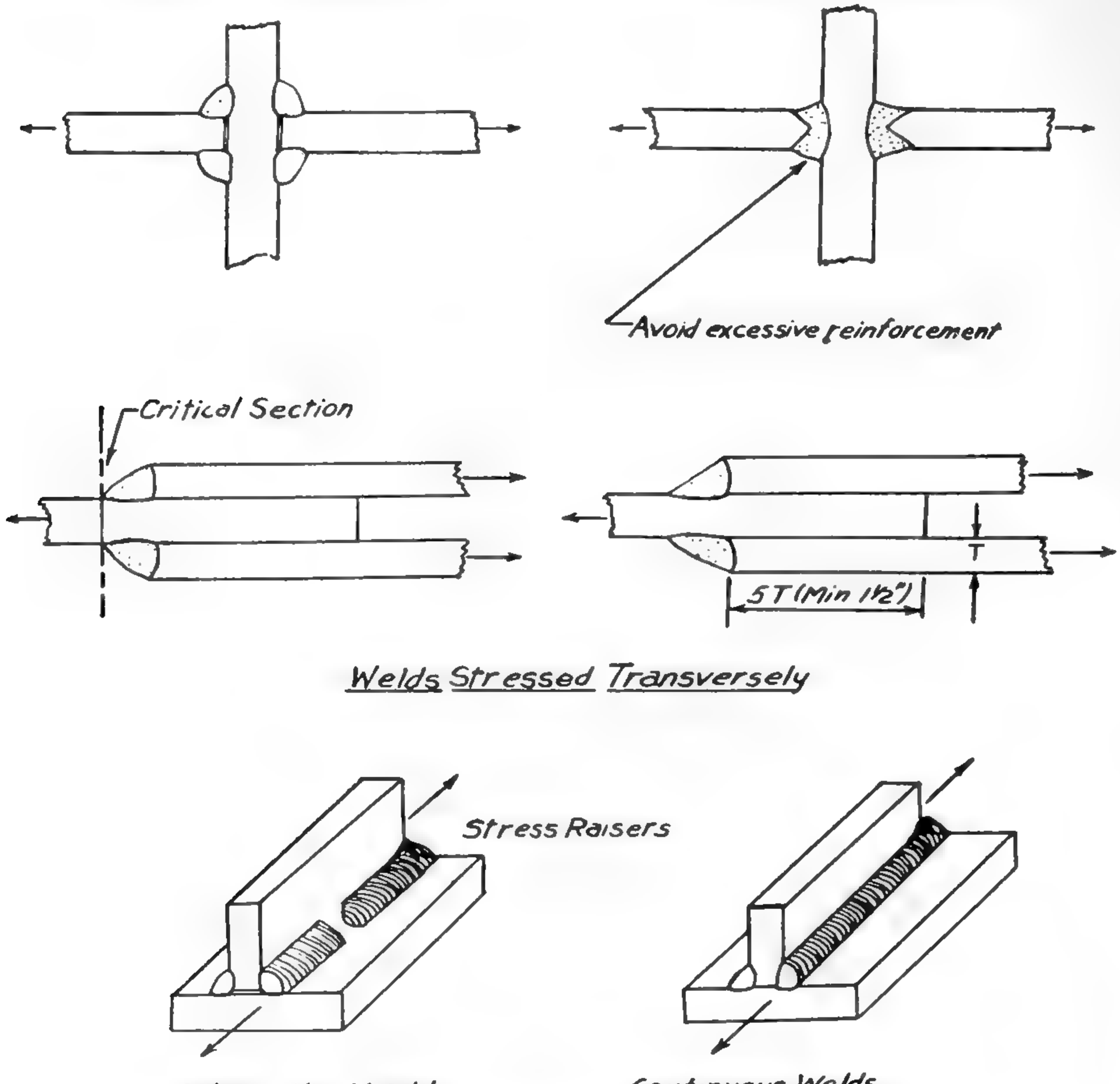


Fig. 3.—Unsatisfactory and Satisfactory Joints for Dynamic Loading

type. Slot welds are permitted only when loads are essentially of static nature.

Splices

Web and Flange Splices.—In the very early stages of structural welding, fillet welded strap splices for web and flanges were required for girder assembly, while butt welding was either ruled out or not depended upon to carry the full stress.

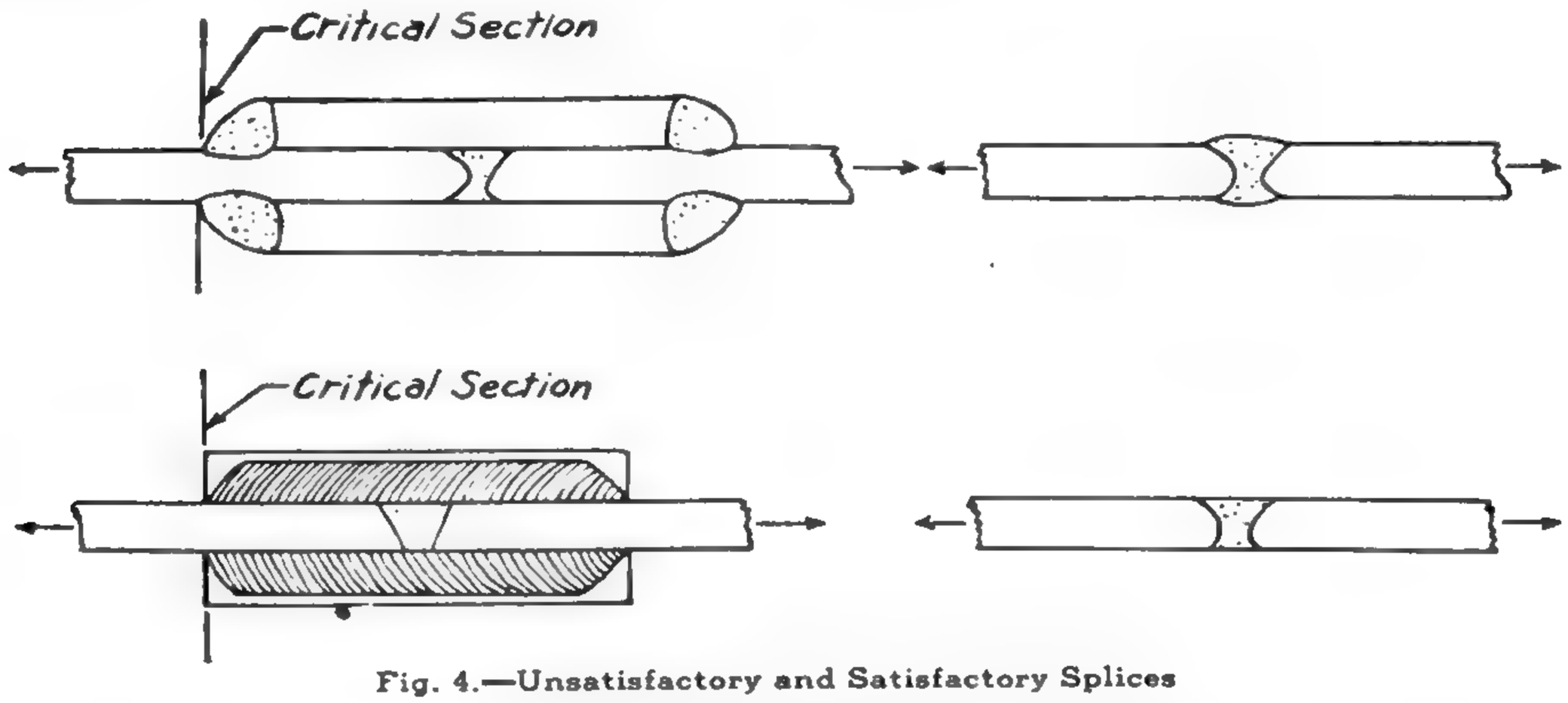


Fig. 4.—Unsatisfactory and Satisfactory Splices

Fillet-welded splice straps actually reduce the fatigue strength of a butt joint.
A butt weld is preferred for fatigue resistance. Removal of reinforcement by grinding or machining to produce smooth and flush surface is desirable, but expense of finishing is seldom warranted.

However, it was soon realized that the butt joint was far more efficient and the requirements were reversed. While the AWS Bridge Specifications have abandoned this restriction against butt welds they do emphasize the necessity of employing a carefully controlled procedure and sequence of welding for splicing rolled beams and built-up plate girders to insure against serious shrinkage stresses and deformations.

The specifications require that all shop splices in each component part be made and that that component be completely assembled before it can be welded to the other parts of the structure. In making butt-welded splices in rolled shapes and in built-up sections, it is mandatory that the sequence and procedure of welding be such that while the weld and the heated base metal are contracting in cooling at any point, any parts of the member that would furnish restraint against such contraction can move, shrink or deform sufficiently to prevent the shrinkage of the heated part from producing harmful effects. As an example of such provisions there is cited the welding of the thinnest member (usually the web) prior to welding the heavier elements; also the use of a backstep sequence and of preheating under some circumstances. The value of the latter cannot be overemphasized and when properly organized is not unreasonably expensive.

The most common practice is to use the double-vee weld for all web splices and for shop welded flange plates except where double-U welds would be more economical. Single-vee or single-U-groove welds with a shallow groove for back welding are used for field splices of flanges to minimize the amount of overhead welding.

Field Splices.—Good design requires that as much of the assembly be performed in the shop as is possible. With trusses over 8 ft. in height the shop welding would, in most cases, be confined to the assembly of individual members because of shipping restrictions. The entire assembly of the trusses would be in the field.

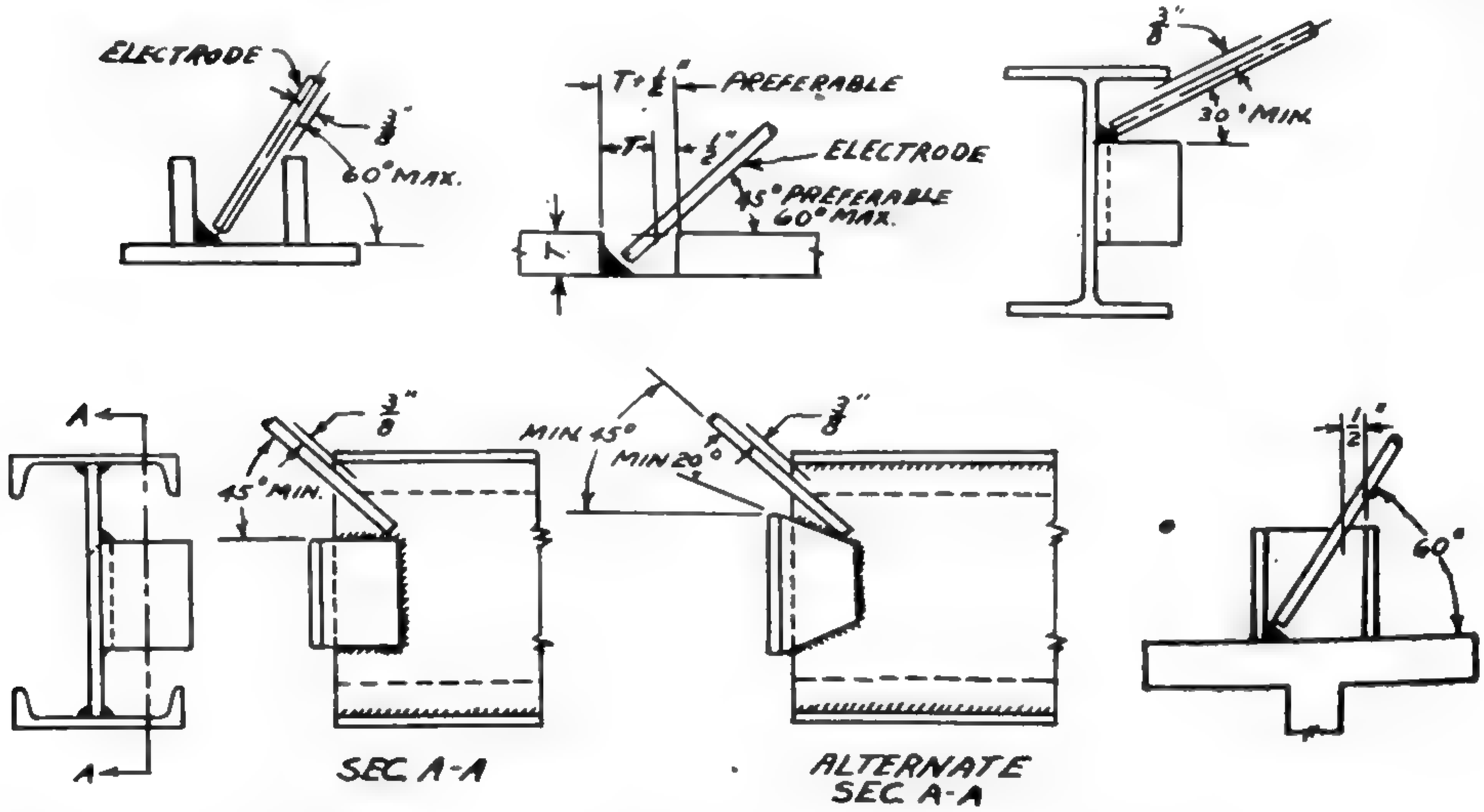
In the case of plate girders it is often possible, for spans of 130 ft. and under, to ship the girders completely assembled. This reduces the field welding to a minimum and usually effects a saving in cost.

Where field splices are unavoidable, as in the case of a long, continuous girder,

they should be located at the points of contraflexure or at least at points where the bending moment and consequent flange stress are low. Abutting parts should be carefully match-marked in the shop and erected on falsework if possible. This latter practice is seldom an expensive item. The upper and lower flange splices are sometimes staggered, the splices being located in the direction of decreasing tension, although this does not seem to exert any appreciable effect.

Camber in Built-up Girders

When it is desirable to leave a residual camber in any built-up simple plate girder some additional camber should be laid out in cutting the web plate to shape. This is because in welding the stiffeners to the compression or top flange (not to the lower or tension flange which is fitted only) some of the camber will be lost by the *pulling in* action of the shrinkage at the upper flange.



NOTE: Information shown for use by designer only.
When materials of different thicknesses are welded the optimum electrode angles vary from those shown to permit the heavier piece to receive more heat.

Fig. 5.—Clearances for Welding

While the sequence of such splicing is determined frequently by convenience in handling and erection, it is generally left to the discretion of the engineer in charge. Although heretofore there has been some opinion that by welding the compression flange first, the tension flange next, and then the web, it was possible to create only compressive stresses in the flanges, experience has shown that reasoning to be fallacious. It is generally preferable to weld the web first, rather than to wait until it is restrained by the welding of the flanges.

A semicircular opening is made in the web opposite the line of the flange splice in order to permit the introduction of the electrode for a complete weld across the flanges on the inside.

Design Details.—Figures 1 to 4, inclusive, illustrate various joints and the correct or incorrect manner of detailing.

Figure 5 illustrates various means of detailing to provide sufficient clearances for welding.

These design requirements (particularly the provisions of Table 1) appear to be much more complex than those of the usual specifications for riveted bridges. It should therefore be noted that:

1. Logic and economy require that similar distinctions, based on probabilities, be recognized in the design of all bridges regardless of the type of fastenings.

2. The system does not (except in rare instances) call for any more work

in the computation of stresses than do the older types of specification.

3. Several of the design formulas in Table 1 (following the word *but*) merely express in formula terms the textual matter of older specifications or the common sense of the situation.

4. Once the live load stresses have been calculated, the application of the several formulas is extremely simple.

Statement 4 is borne out by the complete working out of several typical cases in Appendix A of the AWS Bridge Specification. That Appendix also contains, for the student, an exposition of the application of fatigue test results in bridge design, and a graphical exposition of the several formulas of Table 1.

Further data and discussion pertinent to the fatigue strength of structural joints, and the application thereof to design, will be found in the references shown in the bibliography at the end of this chapter.

Highway Bridge Loadings

Practically all Highway Bridge loadings are now based on the *H principle* as adopted by the American Association of State Highway Officials and approved by the U. S. Public Roads Administration.

There are two general classifications of loadings, the *H* and the *H-S* with several subdivisions therein:

H Loadings.—The *H* loadings are illustrated in Figs. 6 and 7. They consist of a two-axle truck or the corresponding lane loading. The *H* loadings are designated *H* followed by a number indicating the gross weight in tons of the standard truck.

H-S Loadings.—The *H-S* loadings are illustrated in Figs. 8 and 9. They consist of a tractor truck with semi-trailer or of the corresponding lane loading. The *H-S* loadings are designated by the letter *H* followed by a number indicating the gross weight in tons of the tractor truck and the letter *S* followed by the gross weight in tons of the single axle of the semi-trailer or of the corresponding lane loading. The variable axle spacing has been introduced in order that the spacing of axles may approximate more closely the tractor trailers now in use. The variable spacing also provides a more satisfactory loading for continuous spans, in that heavy axle loads may be placed on adjoining spans to produce maximum negative moment.

Classes of Loadings.—Highway loadings are divided into five classes: *H20, H15, H10, H20-S16* and *H15-S12*. Loadings *H15* and *H10* are 75 and 50%, respectively, of loading *H20*. Loading *H15-S12* is 75% of loading *H20-S16*. If loadings of weights other than those designated are desired, they can be obtained by proportionately changing the weights shown for both the standard truck and the corresponding lane loads.

Minimum Loading.—For truck highways, or for other highways which carry heavy truck traffic, the minimum live load is the *H15-S12* loading.

In explanation of the derivation of the lane loadings, the *H* lane loading approximates the truck train loading included in the 1935 AASHO Specifications. The *H15-S12-44* lane loading approximates the *H15* standard truck followed and preceded by 11 $^{1}/_{4}$-ton trucks spaced 30 ft. apart (between axles). The *H20-S16-44* lane loading approximates the *H20* standard truck followed and preceded by 15-ton trucks spaced 30 ft. apart (between axles).

Traffic Lanes.—The lane loadings or standard trucks are assumed to occupy traffic lanes, each having a width of 10 ft. corresponding to the standard truck clearance width. Within the curb-to-curb width of the roadway, the traffic lanes are assumed to occupy any position which will produce the maximum stress, but which will not involve overlapping of adjacent lanes, nor place the center of the lane less than 5 ft. from the roadway face of the curb.

Standard Trucks and Lane Loads.—The wheel spacing, weight distribution, and clearance of the standard *H* and *H-S* trucks are shown in Figs. 6 and 8 and corresponding lane loads are shown in Figs. 7 and 9.

Each lane loading consists of a uniform load per linear foot of traffic lane combined with a single concentrated load (or two concentrated loads in the case of continuous spans) so placed on the span as to produce maximum stress. The concentrated loads are considered as uniformly distributed across the lane on a line normal to the center line of the lane. For the computation of moments and shears, different concentrated loads are used as indicated in Figs. 7 and 9. The

TABLE 1—PERMISSIBLE UNIT STRESSES FOR WELDED

	Loading Producing Maximum Stress		Base Metal In Axially Stressed Members Spliced or End-Connected by Fillet or Plug Welds		
	In Railway Bridges	In Highway Bridges	Form. No	Max. Stress	Required Sectional Area
A	Short Critical Loading (100 feet or less of loaded single track.)		1	Tension	$A = \frac{\text{Max.} - {}^2/_3\,\text{Min.}}{7500}$ but $\leqq \frac{\text{Max.}}{10{,}000}$ $\leqq \frac{\text{Min.} + {}^1/_2\,\text{Min.}}{p}$
			2	Compression	$A = \frac{\text{Max.} - {}^2/_3\,\text{Min.}}{7500}$ but $\leqq \frac{\text{Max.} - {}^1/_2\,\text{Min.}}{p}$ $\leqq \frac{\text{Max.}}{p}$
B	Longer Critical Loading. (More than 100 feet of loaded single track or any length of two or more tracks.) Use "A" loading if greater area is required thereby.	Short Critical Loading. (Not more than two panels or 60 feet of loaded single lane.)	3	Tension	$A = \frac{\text{Max.} - {}^2/_3\,\text{Min.}}{10{,}500}$ but $\leqq \frac{\text{Max.}}{14{,}000}$ $\leqq \frac{\text{Min.} + {}^1/_2\,\text{Min.}}{p}$
			4	Compression	$A = \frac{\text{Max.} - {}^2/_3\,\text{Min.}}{10{,}500}$ but $\leqq \frac{\text{Max.} - {}^1/_2\,\text{Min.}}{p}$ $\leqq \frac{\text{Max.}}{p}$
C		Longer Critical Loading. (More than two panels or 60 feet of loaded single lane or not more than two panels or 60 feet of loaded two lanes.) Use "B" loading if greater area is required thereby.	5	Tension	$A = \frac{\text{Max.} - {}^2/_3\,\text{Min.}}{15{,}000}$ but $\leqq \frac{\text{Max.}}{18{,}000}$ $\leqq \frac{\text{Min.} + {}^1/_2\,\text{Min.}}{p}$
			6	Compression	$A = \frac{\text{Max.} - {}^2/_3\,\text{Min.}}{15{,}000}$ but $\leqq \frac{\text{Max.} - {}^1/_2\,\text{Min}}{p}$ $\leqq \frac{\text{Max.}}{p}$
D		Loading in more than two panels or 60 feet of two or more lanes	Normal Unit Stresses		

A = Required Effective Area; p = allowable unit compressive stress as prescribed by the general specifications for the type of member involved: the capacity of a full butt

Required Effective Weld Areas in All Members and Parts

Form. No.	Type of Weld	Max. Stress	Required Weld Area	Form. No.	Type of Weld	Max. Stress	Required Weld Area
7	Butt	Tension	$A = \frac{\text{Max.} - {}^1/_2\,\text{Min.}}{13{,}500}$ but $\leqq \frac{\text{Max.}}{18{,}000}$	9	Butt	Shear	$A = \frac{\text{Max.} - {}^1/_2\,\text{Min.}}{9000}$ but $\leqq \frac{\text{Max.}}{13{,}000}$
8	Butt	Compression	$A = \frac{\text{Max.} - \text{Min.}}{18{,}000}$ but $\leqq \frac{\text{Max.}}{p}$	10	Fillet or Plug	Shear	$A = \frac{\text{Max.} - {}^1/_2\,\text{Min.}}{7200}$ but $\leqq \frac{\text{Max.}}{12{,}400}$
11	Butt	Tension	$A = \frac{\text{Max.} - {}^1/_2\,\text{Min.}}{15{,}000}$ but $\leqq \frac{\text{Max.}}{18{,}000}$	13	Butt	Shear	$A = \frac{\text{Max.} - {}^1/_2\,\text{Min.}}{10{,}000}$ but $\leqq \frac{\text{Max.}}{13{,}000}$
12	Butt	Compression	$A = \frac{\text{Max.} - {}^8/_{10}\,\text{Min.}}{18{,}000}$ but $\leqq \frac{\text{Max.}}{p}$	14	Fillet or Plug	Shear	$A = \frac{\text{Max.} - {}^1/_2\,\text{Min.}}{10{,}000}$ but $\leqq \frac{\text{Max.}}{12{,}400}$
15	Butt	Tension	$A = \frac{\text{Max.} - {}^1/_2\,\text{Min.}}{18{,}000}$ but $\leqq \frac{\text{Max.}}{18{,}000}$	17	Butt	Shear	$A = \frac{\text{Max.} - {}^1/_2\,\text{Min.}}{12{,}000}$ but $\leqq \frac{\text{Max.}}{13{,}000}$
16	Butt	Compression	$A = \frac{\text{Max.} - {}^1/_2\,\text{Min.}}{18{,}000}$ but $\leqq \frac{\text{Max.}}{p}$	18	Fillet or Plug	Shear	$A = \frac{\text{Max.} - {}^1/_2\,\text{Min.}}{12{,}000}$ but $\leqq \frac{\text{Max.}}{12{,}400}$

Normal Unit Stresses.

weld in compression being treated as identical with that of the connected material. "Max." and "Min." refer to total stresses. "Max." is the numerically greater stress.

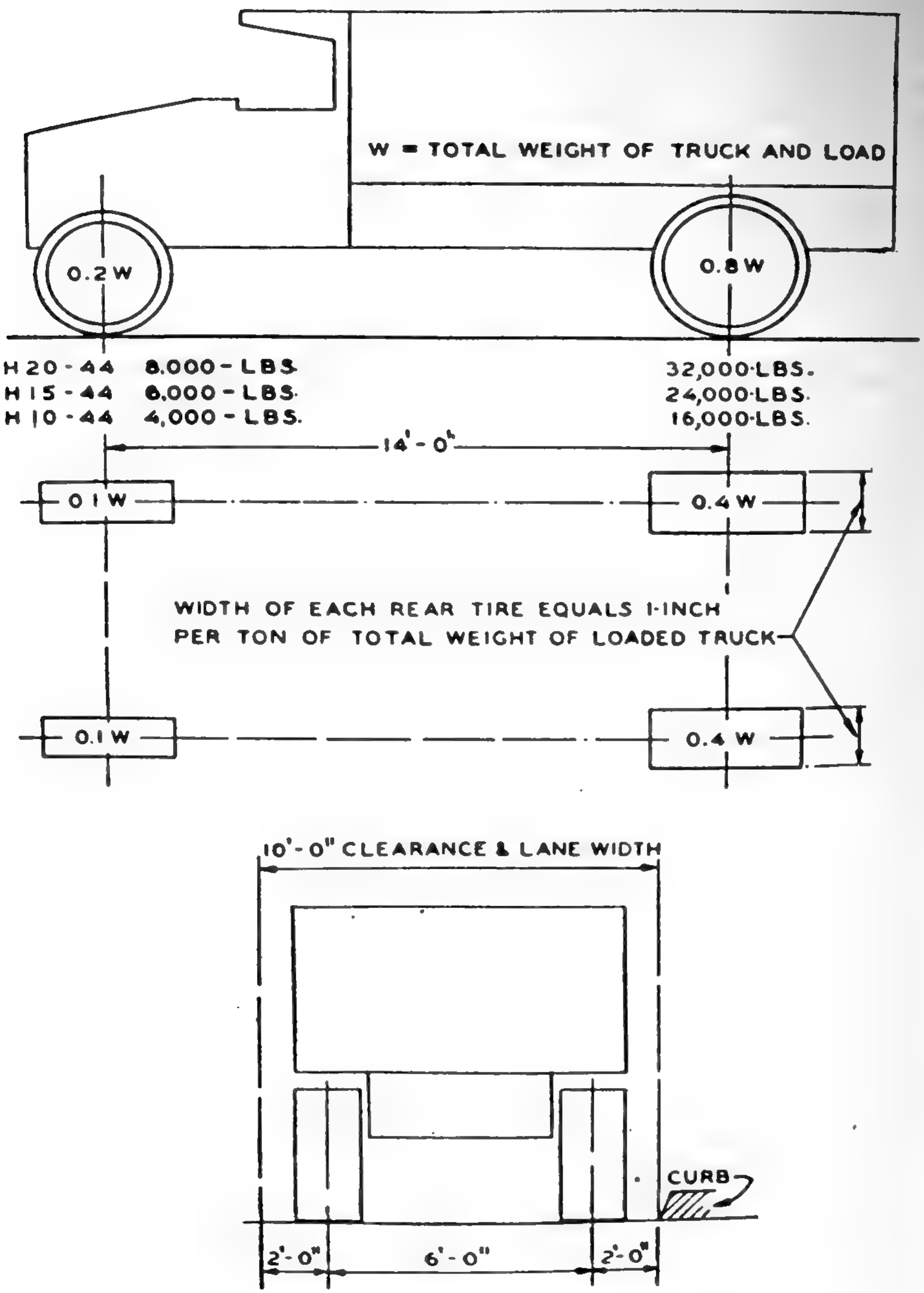


Fig. 6.—Standard H Truck Loads

lighter concentrated loads are used when the stresses are primarily bending stresses and the heavier concentrated loads are used when the stresses are primarily shearing stresses.

Number and Position, Traffic Lane Units.—The number and position of loaded lanes, whether lane loading or truck loading, are such as to produce the maximum stresses and are subject to the following reductions:

One or two lanes	None
Three lanes	10%
Four or more lanes	25%

The cars are of one of the classes shown in Fig. 10. The class is designated by a numeral indicating the total loaded weight of each car. The uniform load per foot of track following or preceding electric cars should be the uniform load corresponding to the class of highway loading specified (640 lb. per linear ft. for *H20* loading). The electric railway loading is assumed to occupy 10 ft. of the roadway width.

For freight car loading, one of the classes of loading shown in Fig. 8 may be assumed in the absence of more exact data.

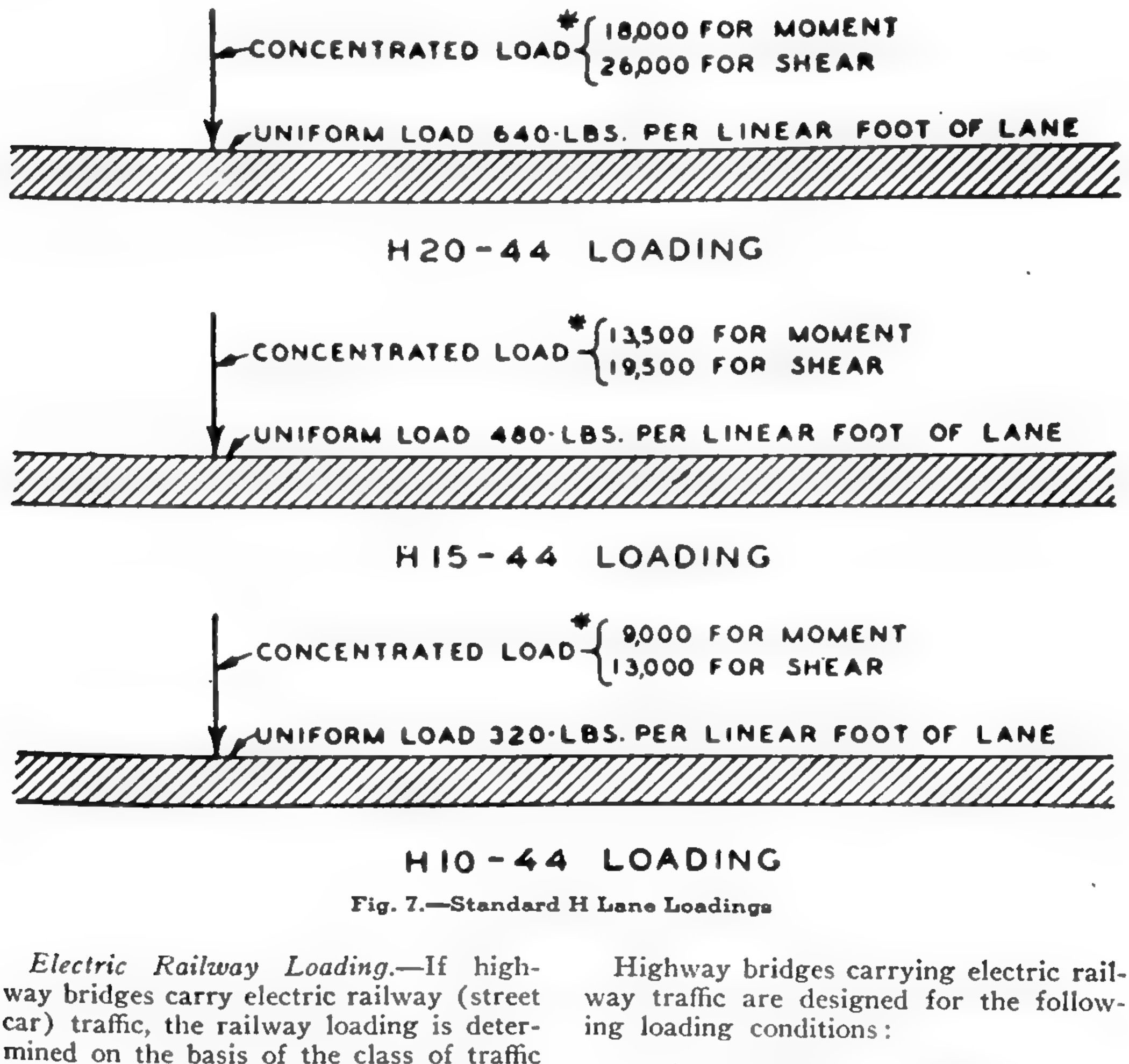


Fig. 7.—Standard H Lane Loadings

Electric Railway Loading.—If highway bridges carry electric railway (street car) traffic, the railway loading is determined on the basis of the class of traffic which the bridge may be expected to carry. When not otherwise specified, the electric railway loading on each track is assumed to be a train of two electric cars followed by, or preceded by, or both followed and preceded by, a uniform load.

Highway bridges carrying electric railway traffic are designed for the following loading conditions:

(1) The highway loading on any portion of the roadway area, including that portion occupied by the railway.

(2) The electric railway loading on the car tracks and the highway loading on the remaining traffic lanes.

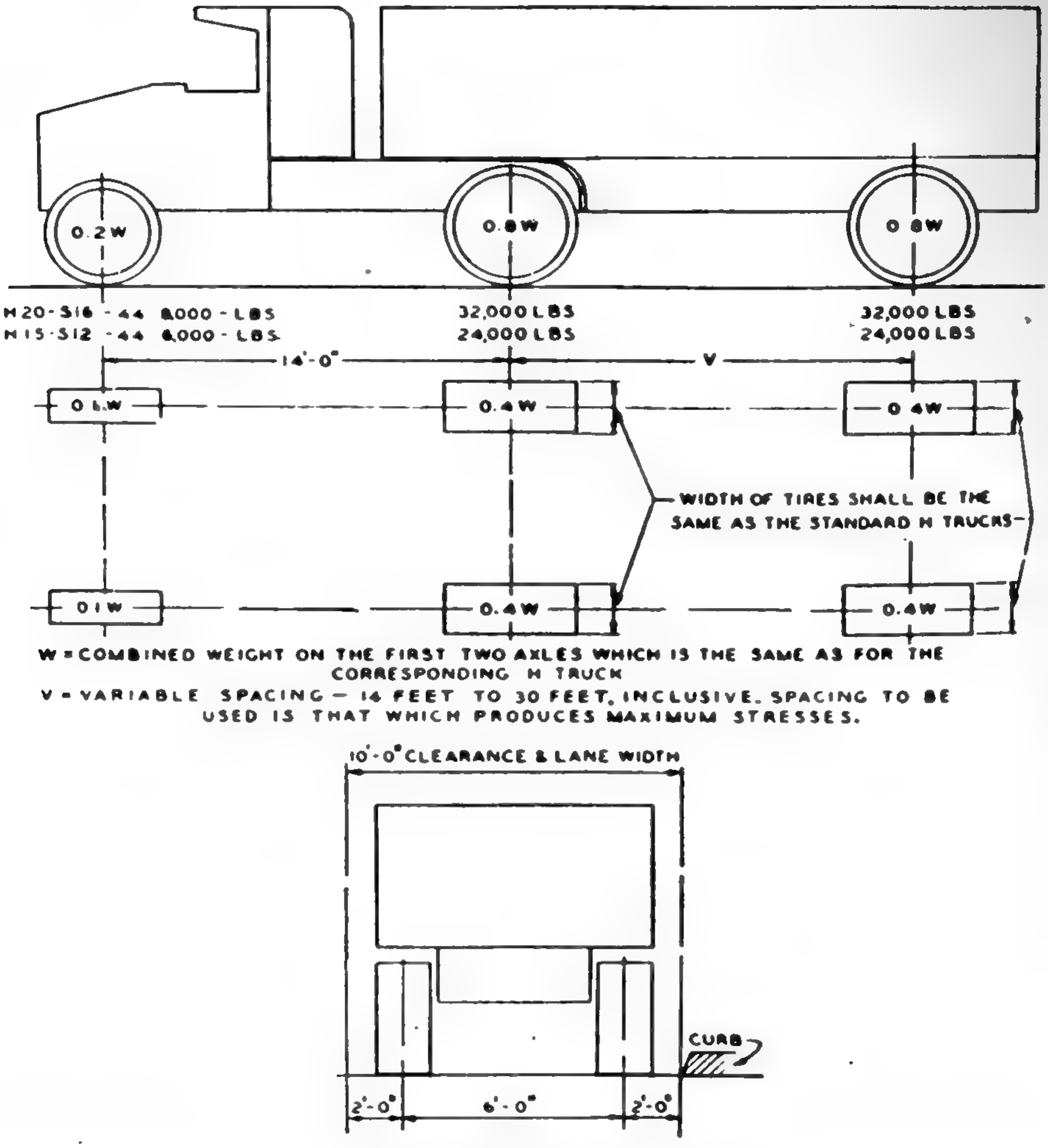


Fig. 8.—Standard H-S Truck Loads

Railroad Bridge Loadings

The basic loading from which all railroad bridge stresses are calculated is known as the Cooper's E system. For many years, the *E60* was used on most of the more prominent lines; this is basically two 213-ton locomotives and tenders followed by a uniform train load of 6000 lb. per foot.

Figure 11 is a diagrammatic tabulation of the Moment Table for Coopers *E60* Loading, and is explained as follows:

Line 1—Summation of loads from uniform load (*R*).
Line 2—Summation of loads from wheel No. 1 (*L*).
Line 3—Number of each wheel from wheel No. 1.
Line 4—Amount of each wheel load in thousand pounds.
Line 5—Distance in feet, center to center of wheels.
Line 6—Distance of any wheel, or the head of uniform load, from wheel No. 1.
Line 7—Distance of any wheel from head of uniform load.

Line 8—Summation of moments of all wheels to right of any wheel, including the wheel in question, about head of uniform load.

Lines 9 to 25, inclusive—Summations of moments of all wheels to left of stepped line (including wheel on left of value) about the wheel just above the heavy vertical stepped line on each line.

The values to the right of the stepped lines are moments about the stepped lines, including wheel to the right of moment value given.

At the present time, and for some time past, the principal railroads of the U. S. have designed for what would be the equivalent of an *E72* system of loading. To convert the tabulated moments, etc., for *E60* loading it is only necessary to multiply them by 1.2. In all cases, linear distances remain the same.

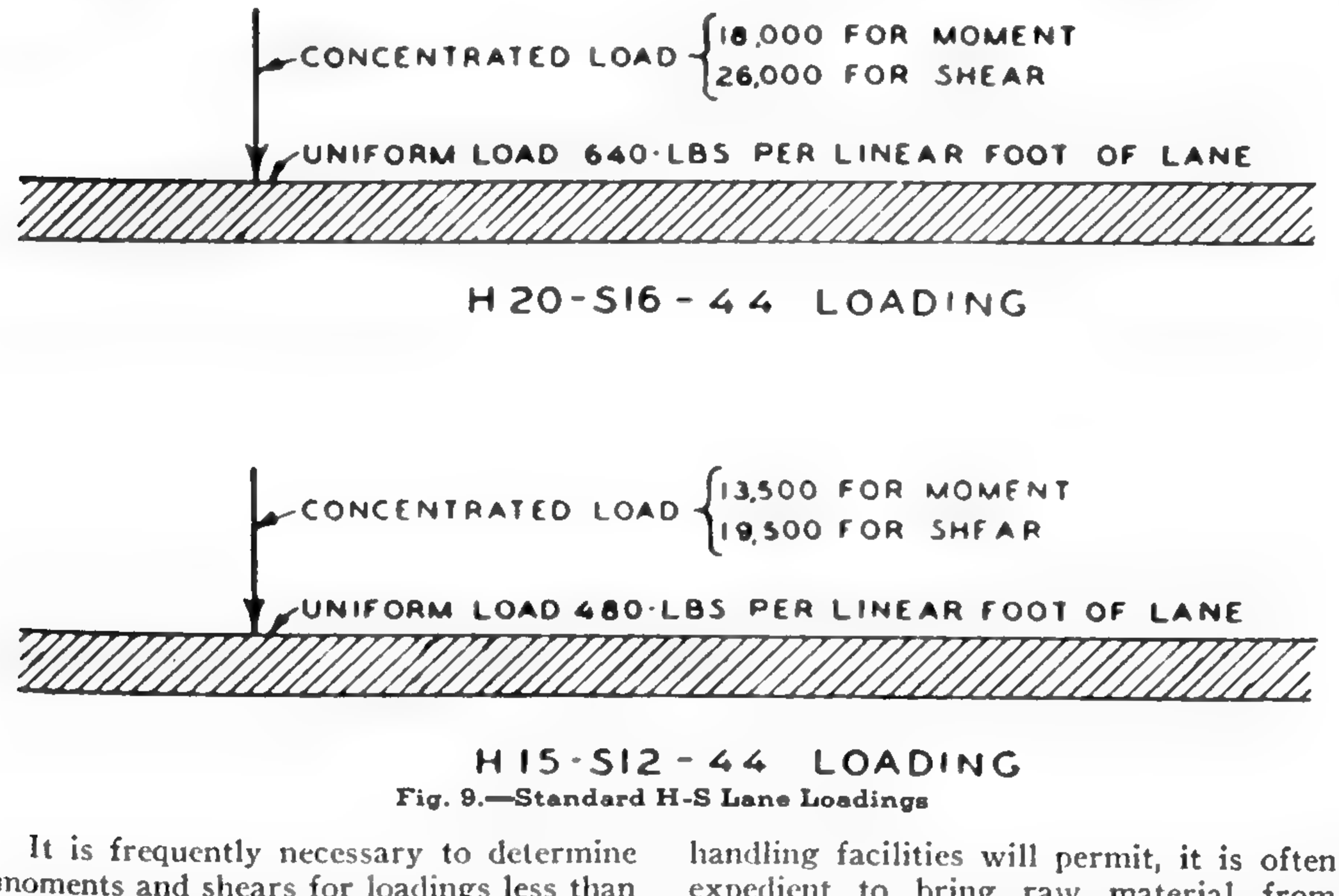


Fig. 9.—Standard H-S Lane Loadings

It is frequently necessary to determine moments and shears for loadings less than *E60*. For this it is only necessary to multiply the tabulated values by the proportion that the load in question bears to *E60*. Thus

For *E50* loading multiply by 0.833.
For *E40* loading multiply by 0.667.
For *E30* loading multiply by 0.500.
For *E25* loading multiply by 0.416.

Impact.—In railroad bridge design, as in highway bridge design, the impact factor is still somewhat of a controversial question. Exhaustive studies and tests have been made with no complete unanimity of opinion resulting.

The AREA produced the following formula which is in general use but by no means universal:

$$I = K\left(\frac{l}{l+d}\right)^2$$

in which

I = Impact factor
d = Dead load per sq. ft.
l = Live load per sq. ft.
K = Coefficient, conservatively figured as 1.

WORKMANSHIP

Fabrication and Erection Methods, and Procedures

If the shop layout, organization and handling facilities will permit, it is often expedient to bring raw material from storage, cut it to length and shape and otherwise prepare it for welding, at the same general location where the welding is to be done. Alternatively, especially when jigs and fixtures are used for fitting and welding, the material is shape cut or otherwise prepared in a nearby location and then moved only once to the fitting and welding location. Usually material flows through a welding fabrication shop in a different manner than

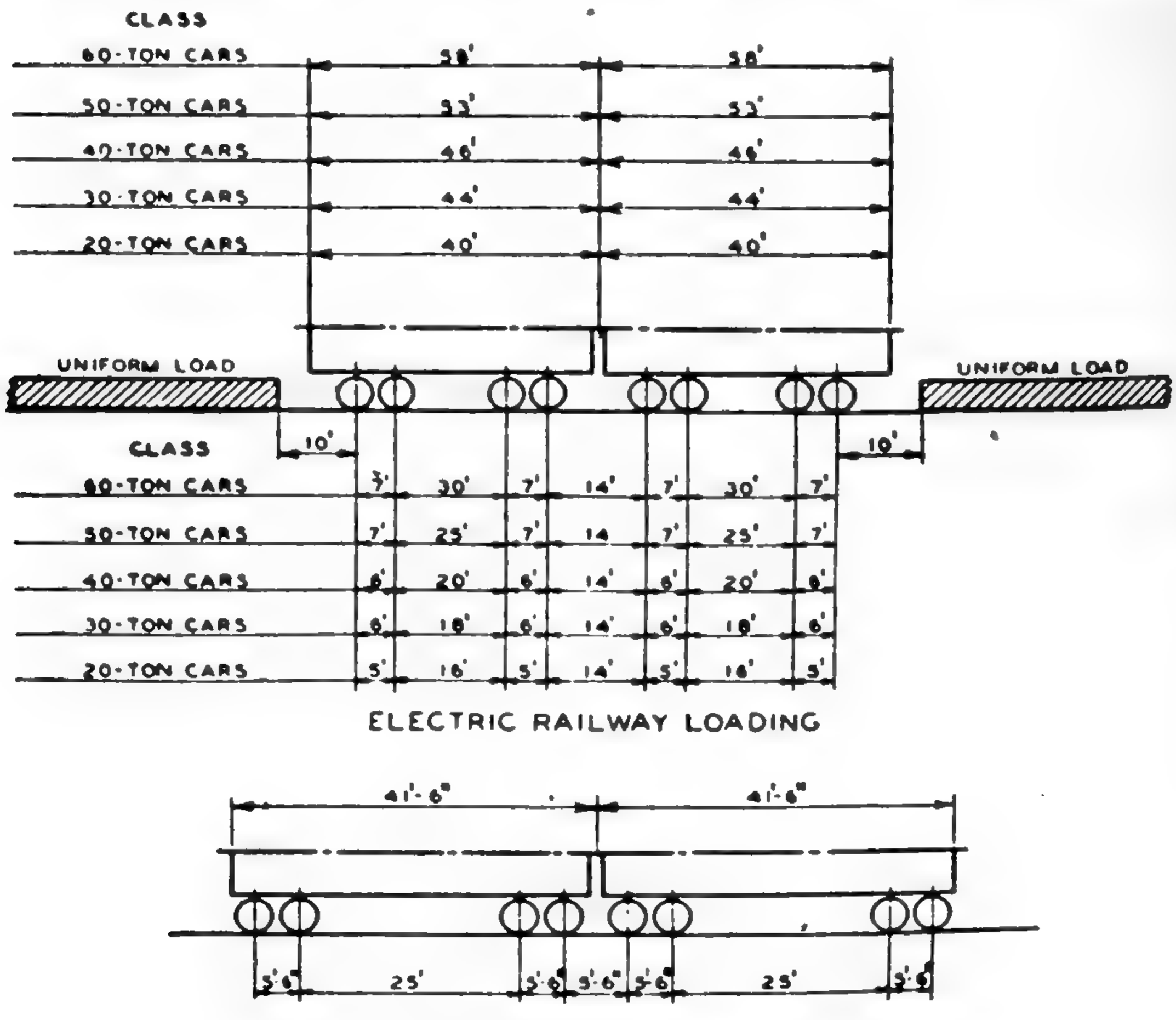
through a riveting shop. Less handling is required and the material remains longer in one location.

To avoid the extra handling and extra operations required for punching erection bolt holes, such holes should be eliminated wherever practical and in any event should be held to a minimum. Where only a very few holes are to be provided in a comparatively heavy piece of material, such holes can be made by piercing with an oxygen-cutting torch and rounding out while still hot by driving a tapered pin in the hole.

Sometimes, for example in the fabrication of trusses, fixtures are provided only for fitting and tack welding, especially when the design is such that no difficulties are to be anticipated from distortion during the subsequent welding with the parts not restrained in a fixture.

When the use of positioning devices is practical and economical, they have the additional advantage of providing for the welding to be done in such a position that it can be executed most easily, thus facilitating good workmanship.

Most of the fabricators undertaking



ELECTRIC RAILWAY LOADING

TOTAL LOADED WEIGHT PER CAR INCLUDING 10 PERCENT OVERLOAD
40 TON CAPACITY - 132,000 LBS.
70 TON CAPACITY - 212,000 LBS.

Fig. 10.—Standard Electric Railway Loading

When a considerable amount of duplication of work is involved, it is not only more economical to use jigs or fixtures for fitting and welding, but this practice facilitates accuracy and helps to insure proper fit-up during erection. welded bridge construction now have a sufficient background of experience to determine the proper welding sequences for use in fabricating such parts as welded girders, to prevent distortion, loss of specified camber, etc. The fundamental

1	426		411	381	351	321		291	271·5	252	232·5	213		198	168	138	108		78	58·5	39	19·5
2	15		45	75	105	135		154·5	174	193·5	213	228		258	288	318	348		367·5	387	406·5	426
3	1		2	3	4	5		6	7	8	9	10		11	12	13	14		15	16	17	18
4	15		30	30	30	30		19·5	19·5	19·5	19·5	15		30	30	30	30		19·5	19·5	19·5	19·5
5	8'	5'	5'	5'	9'	5'	6'	5'	8'	8'	5'	5'	5'	9'	5'	6'	5'	5'				
6	8'	13'	18'	23'	32'	37'	43'	48'	56'	64'	69'	74'	79'	88'	93'	99'	104'	109'				
7	109'	101'	96'	91'	86'	77'	72'	66'	61'	53'	45'	40'	35'	30'	21'	16'	10'	5'				
8	24550	22910	19880	17000	14270	11690	10190	8790	7500	6310	5514	4164	2965	1914	1014	605	292·5	97·5				
9	22420	20860	17980	15250	12670	10240	8830	7530	6340	5240	4524	3325	2275	1374	624	312	97·5					
10	20380	18950	16170	13590	11160	8880	7570	6360	5270	4280	3632	2580	1682	932	331·5	117	97·5					
11	18060	16670	14120	11720	9470	7370	6280	5090	4110	3230	2678	1808	1088	518	97·5	117	331·5					
12	16220	14900	12500	10250	8155	6200	5110	4120	3240	2460	1980	1260	690	270	97·5	312	624					
13	13090	11910	9780	7800	5970	4290	3370	2550	1850	1245	900	450	150	175·5	448·5	838·5	1326					
14	11500	10400	8410	6580	4900	3370	2555	1830	1227	720	450	150	150	423	793·5	1281	1866					
15	10060	9050	7200	5520	3990	2605	1885	1262	755	345	150	150	450	820·5	1288·5	1873	2556					
16	8770	7810	6130	4600	3220	1992	1368	842	432	120	150	450	900	1368	1933·5	2620	3396					
17	6950	6110	4670	3380	2240	1248	780	409·5	156	240	630	1170	1860	2484	3205·5	4044	4980					
18	5240	4524	3325	2275	1374	624	312	97·5														
19	4280	3632	2580	1682	932	331·5	117															
20	3230	2678	1808	1088	518	97·5																
21	2460	1980	1260	690	270																	
22	1245	900	450	150																		
23	720	450	150																			
24	345	150																				
25	120																					

TWO 213 TON ENGINES + 6000 LBS. PER FOOT.
MOMENT IN THOUSAND FOOT POUNDS FOR ONE RAIL.
LOADS IN THOUSANDS OF POUNDS FOR ONE RAIL.

Fig. 11.—Moment Table for Cooper's E60 Loading

factors involved in choosing such sequences are discussed in other chapters of this HANDBOOK.

The erection of welded bridges proceeds in very much the same manner as for riveted bridges. The general trend in all steel bridge construction toward prefabrication and subassembly of larger sections of girders and trusses is particularly applicable to welded construction.

To avoid excessive and uneconomical use of erection bolts, it is sometimes expedient to follow along with the field welding more closely behind the erection and fitting of members than in the case of riveted construction.

In the case of comparatively long superstructures, especially where transverse joists and substringers or metal grating floors are used, it is of great importance to plan the field welding sequence so as to minimize the accumulation of shrinkage in lines of continuous members, which may cause lateral bending of floor beams or buckling of other longitudinal members by an accumulation of shrinkage distortions or loss of dimension.

Provisions for shop and field painting have an important bearing upon the economy of welded bridge construction and under some circumstances they can exert an influence upon the quality of workmanship. The best practice is to omit all painting in the shop and apply the primer coat of paint, as well as the subsequent coats of field paint, after all of the welding has been done during erection. This practice has been looked upon with favor in recent years by bridge engineers for riveted structures as well as welded structures. Prior to the painting in the field, the surfaces of the steel are often conditioned by sandblasting or flame cleaning and dehydrating, to assure the tight adherence of the paint to the metal.

Experience during the war as well as the results of recent tests indicate that if excessive thicknesses of paint film are avoided for the primer coat of paint, it is possible to carry out sound welding on painted surfaces. If this practice is followed, the field inspector should make sure that any excess paint is removed before welding is started. A more detailed discussion of painting will be found in Chapter 47—Buildings.

Basic Imperative Welding Requirements

The workmanship clauses of the AWS Bridge Specifications establish the essentials of a prequalified welding procedure that has been tried and proved through long experience as well as research. Details of technique which are not covered by these provisions, are deemed to be matters properly left to be determined by the practices of the individual fabricator, in the same way that minor details are cared for in specifications for riveted fabrication.

Acceptable contours of welds are shown in the specifications. Where concave fillet welds are used, it is important that operators themselves check the weld size occasionally to guard against undersized welds. However, most of the fillet welds involved in bridge construction are of the slightly convex or flat-face type, for which the usual tendency is to make oversized welds. In the visual inspection of work during its execution, special attention should be given to butt welds at critical locations. An inspection of the groove for proper preparation and fit-up in advance of the welding, and an inspection of root passes and the back chipping or gouging of them to remove slag and imperfections down to sound metal before welding from the opposite side, are usually sufficient to insure the making of sound butt welds. The ends of important butt welds at the edges of material should be given special attention.

Engineers who are accustomed only to riveted construction are sometimes surprised to find that a more extensive application of corrective measures is permitted by specifications for welded structures. The engineer in charge of inspection must necessarily take measures to maintain the standards of workmanship in general, and there is a limit to the amount of correction work which it is advisable to permit in lieu of rejecting a part or member and requiring replacement. However, there are many circumstances under which quite extensive corrections may be permitted without jeopardizing the strength or structural value of a member or frame in any way, provided that the execution of the corrections is properly planned and controlled, and suitable procedures are used. This is possible because the welding process is

a more flexible and versatile one, whereby materials can be joined together intimately to develop their full strength and cross-sectional area, without creating the appearance of being patched.

Suitable methods of correction for use in welded bridge construction are described in the Specifications of the American Welding Society and in other parts of this HANDBOOK.

INSPECTION

General

One of the principal duties of an engineer or inspector in charge of welded construction is to make sure that competent and sufficient supervision and an adequate system of control are provided. for example, has forcibly emphasized the importance of adequate control and supervision of all construction operations, including layout, preparation of material, and fitting, as well as the actual welding.

Methods of Inspection

Non-destructive testing has never been found to be practical in connection with any American methods of bridge construction. In the case of welding, as with other methods, reliability is predicated upon the establishing of suitable construction and welding procedures, the qualification of operators, adherence to the provisions of the established procedures and to the general workmanship requirements of the specifications. The suitability of welding procedures is established by determining that they conform to standard

Fig. 12.—Welded Two-Span Continuous Rigid Frame Highway Bridge

The general trend during recent years in construction practices has been to recognize in contract provisions that good workmanship depends largely upon adequate construction organization, facilities and supervision on the part of the constructor. To this end, some of the State Highway Bridge Departments have required that contractors be prequalified with respect to their background of experience, their facilities and personnel, and their ability to properly supervise the work. A notable example, with particular respect to welding, is the requirements for prequalification of welding fabricators, which has been recently adopted by the Canadian Bureau of Welding, operating under Dominion sponsorship. American experience during the recent war production program in shipbuilding, practices as outlined in the specifications, or by the special qualification of any new or non-standard procedures. A good quality of workmanship and sound construction, in general, are accomplished by adequate supervision and inspection over the various operations of fabrication and erection in order that the essential requirements be met. When procedures are proposed which depart from the standard requirements of the Bridge Specifications of the AMERICAN WELDING SOCIETY, these specifications provide that such newer procedures must be qualified by methods outlined in the appendix of the specifications, which conform to the requirements of the AMERICAN WELDING SOCIETY's *Tentative Standard Qualification Procedure*.

The inspection of welded structural

joints by non-destructive testing is not economically practicable for bridges and is not deemed necessary.

If it is desired to supplement visual inspection with the occasional use of some method for random or spot checking of welds (perhaps especially for important butt welds in quite heavy materials), several methods are available such as radiography by means of X-rays or gamma-rays, magnetic powder testing, and probing or trepanning, which methods are described in Chapter 42. The random use of such methods should be deemed a part of the general system of control over the construction, rather than a proof testing method. Experience has indicated that the most important benefit to be derived from the use of such methods is the psychological effect upon the welder in demonstrating to him the effectiveness of the procedure and technique being used.

Spans include two anchors span, two cantilever arms, and one suspended span.

Fig. 13.—Five-Span Welded Highway Bridge

Probing, trepanning, chipping or gouging to reveal possible defects of welding should not be used indiscriminately by the inspector. He should have good reason to suspect the presence of serious defects before requiring the use of such methods to any marked extent. Such probing methods, if used, should be carried out so as to leave the material in a suitable condition for preparation for rewelding with a reliable technique and procedure.

Requirements of Shop and Field Inspector

The general qualifications and duties of an inspector of welded construction are no different from those for other types of construction. It is not necessary that such an inspector be a skilled welder, but it is essential that he be familiar with the practical aspects of welding as well as its technical aspects. Enough experience in actual welding to appreciate thoroughly the techniques that are employed will be of great assistance to the inspector.

The engineering inspector on welded construction should, of course, perform the same duties as required for other classes of steel construction to determine that all materials are acceptable, dimensions are correct and the fit-up at joints is good. He must satisfy himself that the work has been planned in advance and is properly organized under competent supervision to follow an established procedure and sequence of fabrication and welding. He must ascertain that the welders have all been properly qualified for the work they are to do, and he must check on each welder to see that he understands the established procedure and is following it; also to make sure that he is in good physical condition.

Continuous inspection of every operator is not necessary; occasional obser-

vation, together with a careful check-up on finished welds, has been found adequate, if previous duties as outlined above have been exercised.

Fig. 14.—Single-Span Welded Highway Girder Bridge

The welding inspector should see that none of the welds specified on the design drawings are omitted. The finished welds should be checked for agreement with the plans and specifications, as to size, arrangement, surface contour or convexity, and absence of defects such as cracks, undercutting, overlapping, objectionable irregularities, unfilled craters, pock-marks and other defects. The inspector should discourage the use of oversize fillet welds. Excess welding over that shown on the plans as required for strength or to meet other minimum specification requirements, under some circumstances can be detrimental, and in any event the excess welding constitutes a needless waste of material and labor. In the case of highly important butt welds, especially those subjected to tension, particular attention should be given by the inspector to the checking up of groove dimensions and spacing, prior to welding. Under some circumstances, continuous inspection of the welding of such joints may be necessary, to make sure that the slag is carefully removed between deposition of layers, that the maximum allowable thickness of layer is not exceeded, that the root is thoroughly cleaned and chipped or gouged out before welding is started on the opposite side of the groove from that on which the first pass was made, and to see that other provisions of the welding procedure are strictly followed. It is usually more conducive to good workmanship if the work is laid out and fitted by other workmen in advance of the welding, so that the welder may concentrate on the welding operations and proceed systematically with them.

The duties of the welding inspector may be outlined as follows:

1. Electrodes
   (*a*) To determine that the electrodes used are of such classifications as conform to the requirements of the specifications, and that they have not been damaged by rough handling or improper storage.
   (*b*) To determine that the elec trodes employed for each position of welding, kind of current and other conditions of use are of a suitable classification.
   (See applicable AWS-ASTM Specifications.)
2. Welding Procedures and Sequence, Supervision, and Welders
   (*a*) To determine that the welding procedures proposed for use are standard prequalified procedures, or otherwise that they have been qualified properly by the prescribed tests.
   (*b*) To determine that the welding sequence to be used, together with the proposed procedure, is capable of producing sound welded joints without excessive restraint against weld

Table 2—Welded Bridges

A. Constructed

Town	Road	Name of Bridge	Type	Span, Ft.	Weight of Steel, Lb.	Extent of Welding[b]	Unit Price (Lb.)	Date Completed
Greenwich	Merritt Pky.	Lake Ave.	Rigid frame	2 @ 47	125,000	A	0.08	1939
Trumbull	Merritt Pky.	Trumbull Ave.	Rigid frame	62	288,000	A	0.06	1938
Stratford	Merritt Pky.	Route 8	Rigid frame	62	324,000	A	0.05	1939
Orange	Wilbur Cross Pky.	Derby-Milford Rd.	Rigid frame	2 @ 61	141,000	A	0.08	1940
Hamden	Wilbur Cross Pky.	Dixwell Avenue	Welded girder	126	354,000	A	0.10	1948
Hamden	Wilbur Cross Pky.	Connelly Blvd.	Welded girder	5 @ 115	1,800,000	A	0.10	1948
Hamden	Wilbur Cross Pky.	Skiff St.	Welded frame	2 @ 45	144,000	A	0.097	1947
Hamden	Wilbur Cross Pky.	Whitney Avenue	Girder	119	390,000	A	0.085	1946
Wallingford	Wilbur Cross Pky.	Rt. 5, South	Rigid frame	94	377,000	A	0.09	1946
Wethersfield (see Fig. 13)	Wilbur Cross Pky.	Rt. 5, North	Rigid frame	2 @ 72	200,000	A	0.18	1941
Wethersfield	Wilbur Cross Pky.	Folly Brook Blvd.	Rigid frame	2 @ 72	410,000	A	0.08	1941
Wethersfield (see Fig. 14)	Wilbur Cross Pky.	Jordan Lane	Girder	Suspended span, 80-170-80	1,700,000	A	0.075	1941
East Hartford (see Fig. 15)	Wilbur Cross Pky.	Main Street	Rigid frame	82	316,000	A	0.0675	1940
East Hartford[a]	Wilbur Cross Pky.	Silver Lane	Girder	106	315,000	A	0.10	1948
Vernon[a]	Wilbur Cross Pky.	Rt. 15	Girder	93	308,000	A	0.14	1948
Seymour	Broad St.	Nangatuck River	Rigid frame	58	105,000	A	0.07	1938
Coventry[a]	Willimantic River	Perkin's Corner	Girder	124	214,000	A	0.12	1946
Windham	School Plains Rd.	Shetucket River	Girder	2 @ 100	255,000	A	0.15	1948
East Granby	Floydville	Salmon Brook	Girder	102	160,000	A	0.144	1948
					7,511,000			

B. Under Construction and Proposed

Town	Road	Name of Bridge	Type	Spans, Ft.	Weight of Steel, Lb.	Extent of Welding[b]	Unit Price, Lb.	Status
New Haven	Wilbur Cross Pky.	Rt. 69	Continuous girder	2 @ 125	780,000	A	0.145	Under Constr.
Hartford[a]	Rt. 5	North Meadows, Willimantic Div.	Suspended span	75-107-75	531,000	A	0.19	Bid Recd.
Hartford[a]	Rt. 5	North Meadows, Springfield Div.	Simple and Suspended spans	50-60-90-60	400,000 ±	B	0.13	Bid Recd.
Waterbury[a]	Rt. U.S. 6	Silver St. Viaduct	Continuous I Beams	2 @ 60, 2 @ 75 (6050)	830,000	B	0.145	Under Constr.
Derby[a]	Derby-Shelton	Mill St.	Suspended span	3-Span, 48-67-48	300,000	B		Designed
Seymour[a]	Rt. 67	Bank St., Little River	Welded girder	106	209,000	A		Designed
					3,465,000			

[a] Federal aid. [b] A = All welded; B = Partially welded.

contraction. This is of particular significance in the fabrication of heavy girders and trusses and in making field splices in them; also in any case where extensive areas of plating are involved, as in *battledeck* or other types of metal floor construction, or in the case of a structure with relatively long lines of continuous framing, where shrinkage might be cumulative if suitable provisions are not made to prevent it.

(*c*) To determine that an adequate system of control and supervision of the welding and all related operations has been set up, including the preparation of material and the fitting.

(*d*) To determine that all the welding operators to be employed upon the work have been properly qualified by a responsible bureau or agency.

(*e*) To determine that the welding equipment to be used is of a suitable type and in good operating condition.

3. Preparation of Material and Fitting for Welding

(*a*) To determine that the edge-preparation of material at welded joints is done with sufficient accuracy, and that the material has not been kinked or buckled in handling in such a way as to prevent proper fitting.

(*b*) To determine that the fitting is done within suitable tolerances so that sound welds can be made without difficulty.

4. Execution of the Welding

(*a*) To determine, in general, that the procedure of welding as carried out conforms to that which has been established as qualified.

(*b*) To observe occasionally the work of each welding operator to determine that he understands the procedure to be followed, and to check his ability, especially in the case of his having been out of employment at welding for a period of time.

5. Inspection of Finished Welding

(*a*) To examine every welded joint for compliance with the working drawings with respect to sizes, lengths and locations of welds, and to see that no welds have been omitted.

b) To examine the welding for compliance with standards of workmanship with respect to convexity or concavity of weld surface, surface defects, craters, undercutting, overlapped edges of welds, cracks, etc.

(*c*) To require corrective measures to be taken wherever necessary, in compliance with the methods prescribed by the specifications.

A few typical examples of welded bridges erected by the Connecticut State Highway Department are listed in Table 2 and illustrated in Figs. 12, 13 and 14. A more complete list is available from the American Welding Society on request.

BIBLIOGRAPHY

1. *Fatigue Strength of Welded Joints—A Review of the Literature to October 1, 1936*, W. Spraragen and G. E. Claussen, The Welding Journal Res. Suppl., January 1937.

2. *Calculation and Graphical Representation of the Fatigue Strength of Structural Joints*, The Welding Journal Res. Suppl., February 1942.

3. *Fatigue Strength of Welded Joints—A Review of the Literature to September 1941*, W. Spraragen and D. Rosenthal, The Welding Journal Res. Suppl., September 1942.

4. *Fatigue Strength of Butt Welds in Ordinary Bridge Steel*, The Welding Journal Res. Suppl., May 1943.

5. *Fatigue Strength of Butt Welds in Ordinary Bridge Steel-Maximum Stress Compressive*, The Welding Journal Res. Suppl., January 1945.

6. *Fatigue Strength of Fillet, Plug and Slot Welds in Ordinary Bridge Steel*, The Welding Journal Res. Suppl., July 1945.

7. *Effect of Periods of Rest on the Fatigue Strength of Welded Joints*, The Welding Journal Res. Suppl., September 1946.

8. *Flexural Fatigue Strength of Steel Beams*, W. B. Wilson, The Welding Journal Res. Suppl., August 1948.

9. *Fatigue Strength of Riveted Joints*, Bulletin 302, University of Illinois Experiment Station, May 1938.

10. *Fatigue Tests of Butt Welds in Structural Steel Plates*, Bulletin 310, University of Illinois Experiment Station, January 1939.

11. *Fatigue Tests of Connection Angles*, Bulletin 317, University of Illinois Experiment Station, October 1939.

12. *Fatigue Tests of Welded Joints in Structural Steel Plates*, Bulletin 327, University of Illinois Experiment Station, February 1941.

13. *Fatigue Tests of Commercial Butt Welds in Structural Steel Plates*, Bulletin 344, University of Illinois Experiment Station, October 1943.

14. *Fatigue Strength of Fillet-Weld and Plug-Weld Connections in Steel Structural Members*, Bulletin 350, University of Illinois Experiment Station, March 1944.

15. *Flexural Fatigue Strength of Steel Beams*, Bulletin 377, University of Illinois Experiment Station (to be published).

16. *Fatigue Strength of Fillet-Weld, Plug-Weld and Slot-Weld Joints Connecting Steel Structural Members*, Bulletin 381, University of Illinois Experiment Station (to be published).

17. *Fatigue Strength of Various Details Used for the Repair of Bridge Members*, Bulletin 383, University of Illinois Experiment Station (to be published).

18. *Structural Engineers Handbook*, M. S. Ketchum, McGraw-Hill Book Co., 1924.

19. *Manual of Design for Arc Welded Steel Structures*, LaMotte Grover, Air Reduction Sales Co., 1946.

20. *Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings—Riveted and Arc-Welded Construction*, American Institute of Steel Construction, 1947.

CHAPTER 49

MACHINERY CONSTRUCTION*

THE TERM *machinery* here is taken to mean industrial and agricultural machinery and equipment that is not obviously a container or a pressure vessel.

In view of the fact that there are several times as many industrial establishments making weldments as there are foundries making castings, the old arguments about casting vs. weldments may be accepted merely as history.

The economics of weldments for machinery and equipment involve many factors in the overall cost of manufacture. The first consideration is the equipment available for their manufacture. In large-scale operations, the design may be made without reference to equipment on the assumption that whatever is necessary will be provided. Economically correct design may be produced under these conditions. In smaller scale operations, design must fit the equipment available. Thus a weldment which can be designed so that long run automatic arc welds may be made on a positioner first on one side and then on the other side of the neutral axis in bending may have a welding cost of less than one quarter the welding cost of one designed for many short run manual welds. In case the weldment is warped beyond machining tolerances, straightening is expensive. Where the structure cannot be straightened and low areas must be built up, the operation is still more expensive.

MANAGEMENT OF PRODUCTION OF WELDMENTS

Management of production of weldments is like any other management of production in that it involves application of tools and equipment by men to accomplish a predetermined result. Further, the key to success is in the accurate achievement record which must be kept. Man hours per unit is the most important factor for management to control and steadily achieve reduction in cost. On repeat work this is accomplished by variation of such factors as material handling, methods of cutting and forming, amount of heat used for welding, necessary repairs, furnace treatment, etc. Justification of management above the level of group leader is found in control of costs and their continual reduction in man hours per unit.

In jobbing production where most jobs are different, the plotting of an achievement curve is far more difficult than in the case of manufacturing work. Under these conditions, the individual who makes the estimate should estimate the time in man hours for each operation. Management should then make a record of the actual time for each operation, to plot with the estimate. This will serve as an achievement record for both management and estimating personnel.

No very satisfactory piecework incentive system has been worked out for the production of weldments except where a considerable number of identical operations may be completed during one shift. Where the operation spans several shifts and different operators work on it, such systems become too involved to pay their own way and show a profit.

Skilful use of backlogs between operations, in the production of weldments, will generally improve man-hour production in jobbing work. By such means men are kept doing the same things, always with work ahead to be done. Where there are no backlogs, experience shows that men frequently run out of work in their department and have to be shifted.

MATERIALS

A great variety of materials is avail-

*Prepared by Robt. E. Kinkead, Consulting Welding Engineer.

able for use in welding construction, such as billets, slabs, structural shapes, plates, bars of all descriptions, pipe, forgings, special rolled sections and steel castings. There is a great difference in the price per pound of these materials and certain facts regarding their surface, size, cutting tolerance, etc., have an important bearing on their use. Therefore, it is not only important for the designer to consider rolled steel sections but also to consider such sections in sizes and shapes that will take the base price or as few extras as possible.

Steel companies publish pamphlets listing extras and deductions, quantity differentials, and standard tolerances in thickness, width and length for various rolled steel products. Variations from true flatness are also published and extras for special flatness are quoted on application. It is essential that the designer be familiar with these data in order that he may use the cheapest possible material and still get the proper steel for the purpose.

When using plates for machine construction there are a few things in particular the designer should keep in mind. Up to and including 2 in. in thickness, plates are sheared and there is no charge for cutting. Plates over 2 in. in thickness are oxygen cut for which a charge is made, according to thickness. However, because of possible *shear warp* oxygen cutting is recommended where possible.

The universal mill rolls plates to exact width, within usual mill tolerances (rolls steel in one direction only), consequently on plates over 2 in. in thickness the customer is charged for only two oxygen cuts (such plates are obtainable in widths up to about 60 in.). Plate mills roll steel in both directions and in much wider widths but the customer is charged for four cuts on plates over 2 in. in thickness.

When purchasing steel it is often uneconomical to order individual items cut to size. When two rectangular pieces of the same width are ordered as separate items, and they are made on a universal mill, the customer pays for four cuts across the width of the piece. If the two plates are combined and ordered as one piece, however, the customer pays for only two cuts across the width of the piece, the third cut being made in the customer's shop.

Plates which are not rectangular in shape are called sketches and take a per pound extra based upon the number and shape of the cuts required.

The designer should also bear in mind that oxygen-cutting tolerances on a 3-in. plate is plus $^5/_8$ inch. This tolerance is often not small enough for the user and extra cost is involved in additional cutting or machining by the purchaser before the plate can be used.

There are many opportunities to use semi-finished material such as billets, blooms or slabs in machine construction. Billets have rounded corners which might prevent them from being used for some purposes, but for many others they will serve very well and the finish will not be objectionable.

The surface of slabs is not suitable for machine construction unless the part is to be machined or is in an inconspicuous place, for slabs usually contain roll ragging marks.

Straightness must also be considered in semi-finished material if the pieces are in long lengths because this material is primarily intended for re-rolling and is not required to be straight. Semi-finished material is low in price, and where it will serve the purpose, its use presents an opportunity for reducing the material cost.

Types of Materials Suitable

There are many grades and types of steel and nonferrous metals that can be satisfactorily used in the construction of welded machinery.

The major portion of all-welded machinery is fabricated from materials containing less than 0.30% carbon. Material of this grade has satisfactory physical properties and is readily welded and flame cut.

Many special low-alloy steels are also available which have welding properties comparable to the plain low-carbon steels. These alloys have higher tensile and yield strength than plain low-carbon steels and generally have somewhat better corrosion-resisting properties. It is important to remember, however, that the modulus of elasticity of all steels is approximately the same, consequently where deflection requirements are the design criteria, the higher strengths of the more expensive low-alloy steels are of little importance.

Many high-alloy and medium-carbon steels are being incorporated in machinery designs with excellent success. Knowledge of the weldability of such materials is essential, however, in order to properly design the joints and to satisfactorily fabricate the structure. Figure 1 illustrates a gear ($^1/_2$ diametral pitch, 10-in. face, 32-in. P.D.) fabricated by welding an SAE 4140 forged rim to a mild steel plate and hub. The parts were preheated with a gasoline torch to 600°F. before the rim was welded and after welding was begun it was continued to completion without interruption. This gear is operating successfully and delivers over 17,000,000 in.-lb. torque.

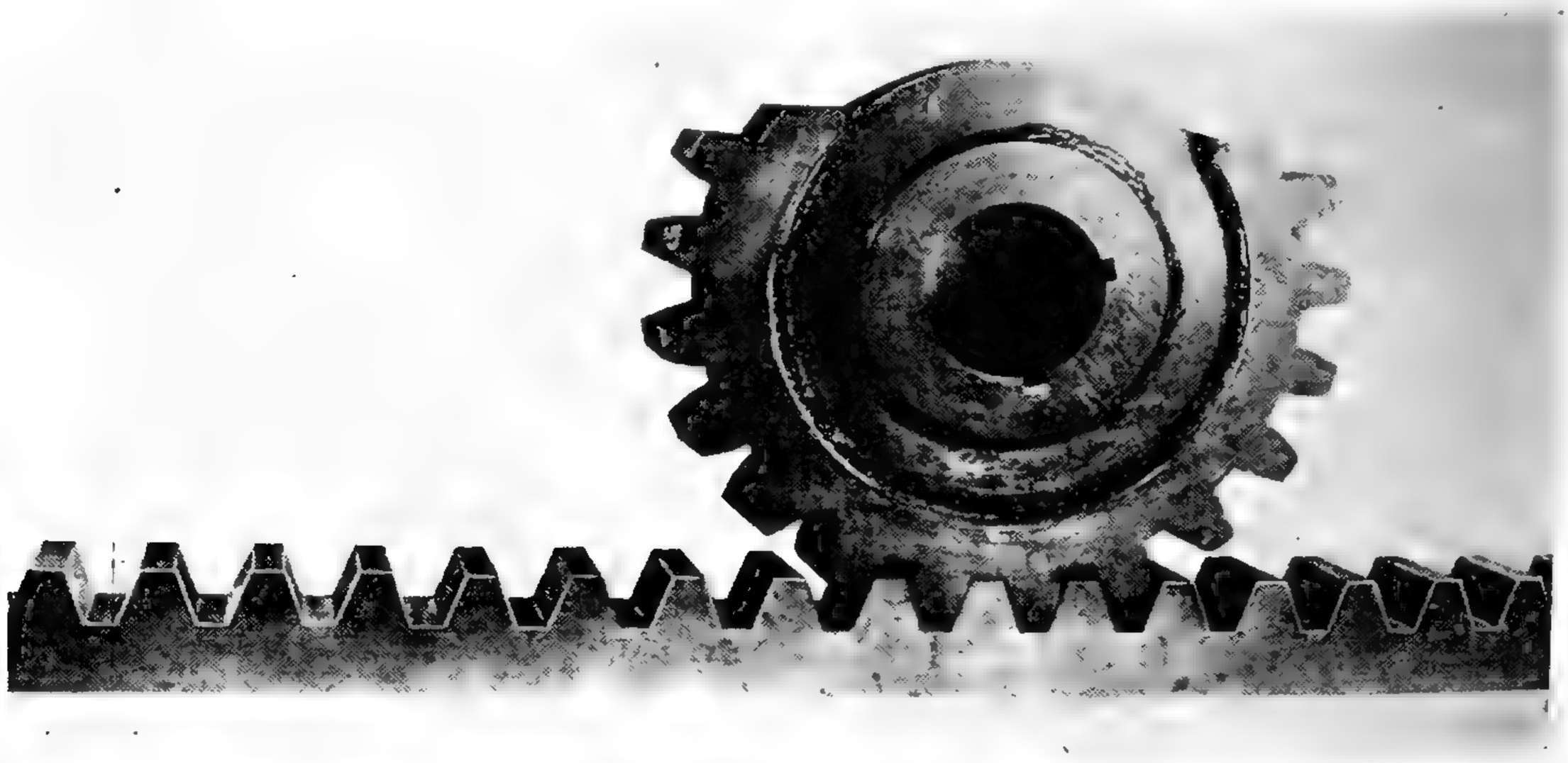


Fig. 1.—Gear Fabricated by Welding

Nonferrous materials such as nickel, Monel, bronze, etc., are also incorporated into machinery designs. Problems of expansion and welding technique are of particular importance in such structures. See individual Chapters on these materials for further information.

Use of Plates

The general use of plates for machinery parts needs no comment. One point the designer should always keep in mind, however, is the economy obtained by forming plates around corners in order to eliminate welding. For example, a rectangular section made by welding four plates together requires four separate welds. The same result might be obtained by bending two plates into angles before welding which would require only two welds. In some cases three corners could be bent, thereby requiring only one weld. Special channels are also more economically made by bending a plate than by welding three plates together. Box sections can be made from such channels by welding closing flanges to them.

Formed sections of this type not only afford economies by reducing the amount of welding but also produce rounded corners which in some cases are still considered essential for good appearance.

Use of Structural Shapes

Structural shapes have a definite field in machinery construction and should be used to the fullest extent. In many cases their use appears to be limited probably because the designers have not yet learned to think in terms of rolled shapes as much as they should or because they are not familiar enough with the variety of shapes available. In many welded structures, sections that can be obtained as rolled shapes have been built up of welded plates. This means considerable flame cutting and welding, whereas many of the rolled sections can be purchased at about the same price per pound as the plate.

Generally speaking, a rolled section is cheapest, a formed section made by bending plates is next, and a welded section is the highest priced. For example, a rolled channel is cheaper than one formed by

bending a plate into a channel, and a bent or formed channel is cheaper than one welded from three plates. A rolled I-beam is also cheaper than one formed by welding three plates.

Box sections which are excellent for resisting stresses of a complex nature are readily fabricated from pairs of angles or channels. The wide range of size of structural members available makes it unnecessary to use formed plate sections except for large size parts.

Use of Pipe and Tubes

One of the most efficient sections available to the welding designer is the pipe or tube. A tubular member has the same resistance to stress in all directions because of the central location of its neutral axis. For resistance to torque, nothing compares dollar for dollar with a tubular section and it may be easily joined to any surface shape by welding.

An example of the use of tubular sections is the eccentrically loaded mandrel extension unit and frame of a rotary bending machine built to bend 12 to 17 in. O.D. pipe, as illustrated in Fig. 2. It is estimated that the use of tubing rather than box or H-beam sections for this structure reduced the weight 22,000–27,000 lb. and 168–198 labor man-hours.

Use of Steel Castings

The combined use of steel castings and rolled sections has proved economical in certain cases. Complicated sections which would require a number of parts and a large amount of welding are often more economically made by casting. This is particularly true if there are a great many sections to be made.

Another case where the use of castings has been advantageous is in the construction of large bosses and bearing blocks for gear cases which otherwise would have had to be cut from large blocks. Figure 3 illustrates a fabricated gear case containing cast steel bearing blocks.

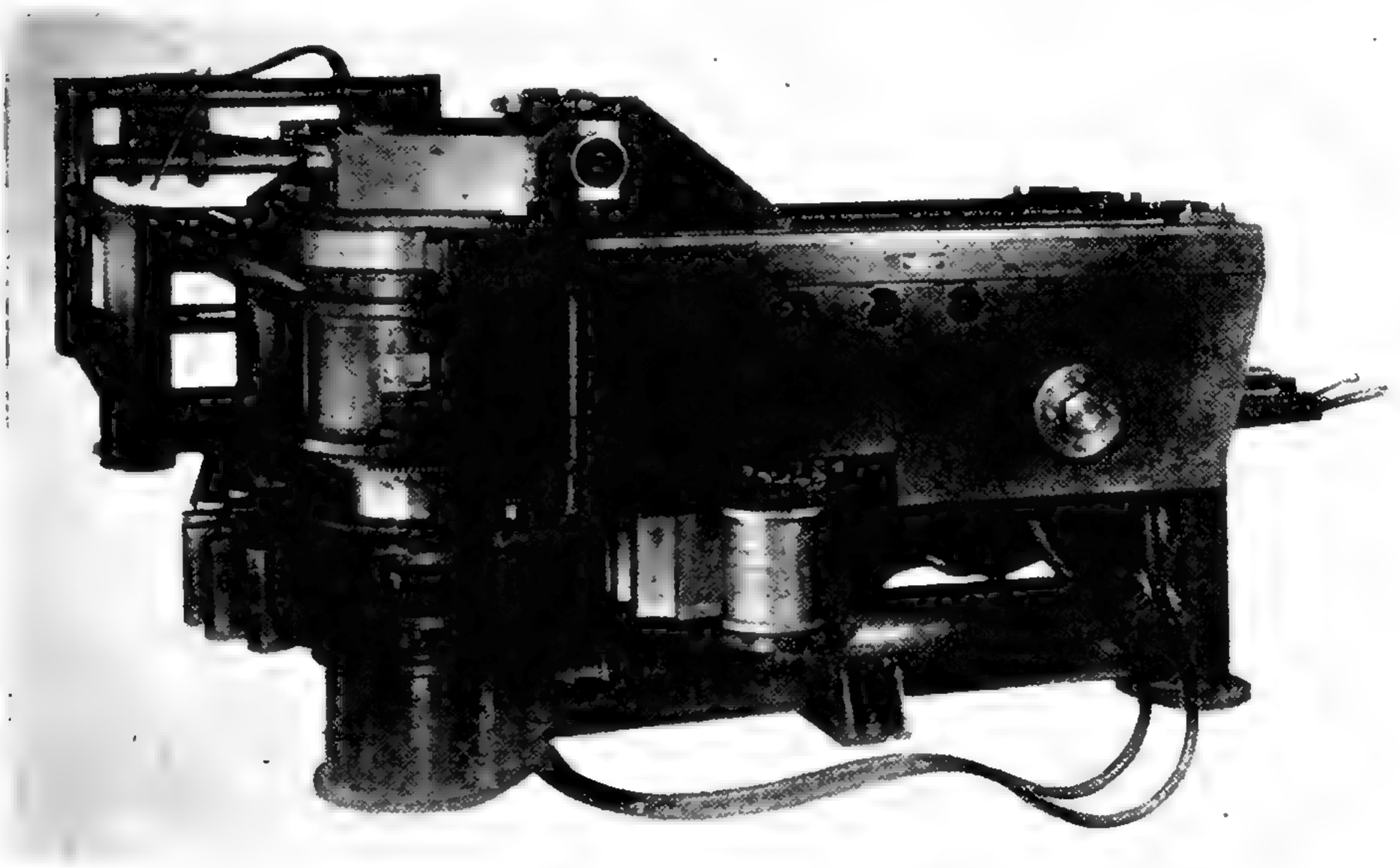


Fig. 2.—Rotating Bending Machine Fabricated by Welding

DESIGN DETAILS

The service life of any welded machine is dependent upon the proper design of the various members and the joints between the members. From a welding viewpoint, the joints are the important factor, consequently it is important that the designer be familar with characteristics peculiar to the different types of joints used.

Stress Analysis of Joints

Two general types of welds are used in

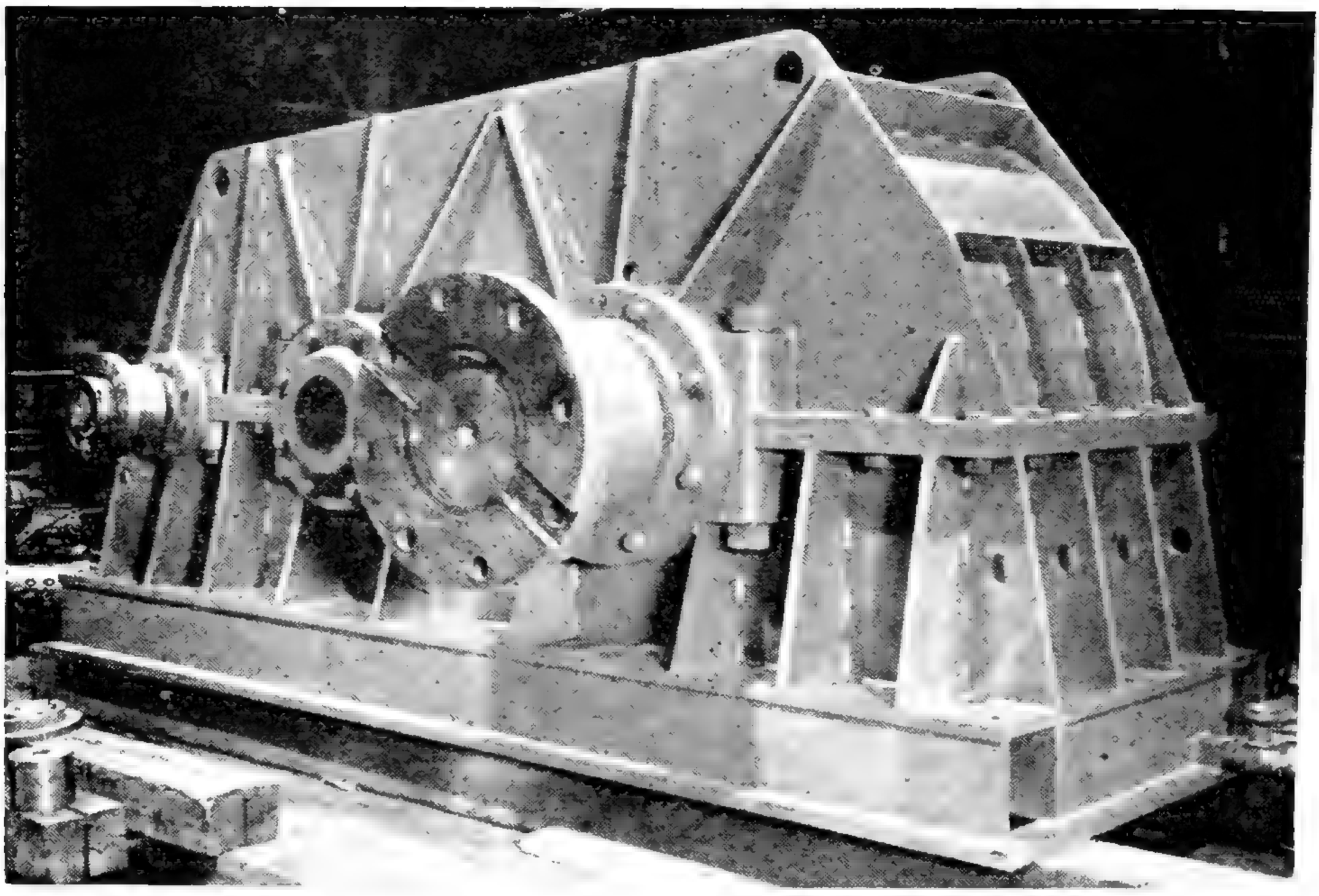


Fig. 3.—Fabricated Gear Case Containing Cast Steel Bearing Blocks

making strength joints on machinery—groove welds and fillet welds.

Tensile and shear stresses for groove welds are usually calculated by dividing the force by the cross-sectional area of the weld. Maximum bending stresses are calculated by dividing the bending moment by the section modulus of the weld. When a combination of tensile, shear or bending stresses is present, they all must be taken into consideration in the usual manner.

Fillet welds are generally considered to be stressed in shear regardless of whether the load is applied parallel or transverse to the weld axis and the stress is calculated by dividing the force by the weld throat area (weld throat = 0.707 × weld size). If a fillet weld is subjected to a combination of shear and tensile stresses acting at right angles to each other the resultant stress may be considered the vector sum of the two stresses (Fig. 4).

Stress Concentrations

Local discontinuities and abrupt changes in the section of a member cause a local bunching of the stresses (stress concentration) at these points and are usually known as stress raisers. The importance of stress raisers and the resulting stress concentrations are dependent upon the ductility of the material and the type of loading.

Stress concentrations in ductile materials subjected to static loads are generally not serious because the metal can yield or flow plastically to neutralize or redistribute the stress. Brittle materials will not flow plastically, consequently there is no redistribution of stress and there is danger of failure occurring at points of stress concentration.

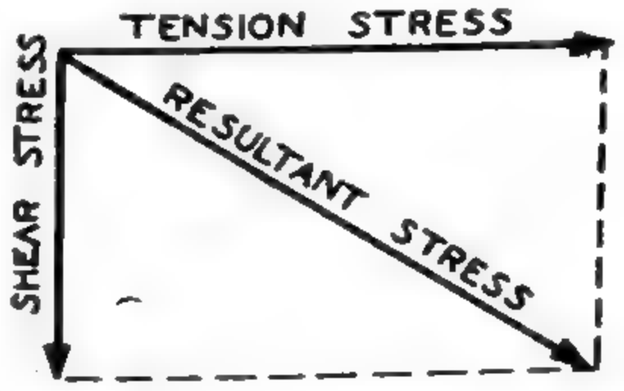


Fig. 4.—Vectorial Addition of Stresses in Fillet Welds

Stress concentrations in members subjected to fatigue loading may produce failures and should be avoided or properly taken into consideration when calculating the size of the member.

A fatigue failure in a machine is governed by two factors: the ability of the material itself to withstand repeated stresses and the existence of points at which the stress exceeds the endurance limit of the material. Stress raisers resulting from sharp corners, fillets, notches, holes, etc., may produce stress concentration factors many times the average stress and unless these peak values are held below the endurance limit ultimate failure in service will result.

In order to prevent fatigue failures from stress concentration, two methods may be used:

1. Eliminate as nearly as possible the stress raisers or causes of the stress concentration.
2. Design the member so that the maximum stresses obtained at the points of stress concentration do not exceed the endurance limit.

Welded joints, because of their character and shape, are often stress raisers. A small hole in a plate will produce a theoretical stress concentration of 3 to 1 and a small gas-hole or slag inclusion is not uncommon in welds. Sharp corners and notches are well-known stress raisers and are obtained with groove welds having incomplete penetration at the heel and toe of a fillet weld, and at points of undercut or reinforcement.

Welded joints on machinery subjected to dynamic loads should be designed with these factors in mind. Stress raisers resulting from the weld's shape should be eliminated as much as possible and high-quality welding should be used.

Residual Stresses

The process of welding is known to produce residual stresses which may reach in magnitude the yield strength of the material. If the structure is loaded in the same direction as the residual stresses, their combination may result in plastic yielding and the actual stresses may greatly exceed the design working stresses.

Residual stresses are also known to cause a structure to warp and twist out of shape during machining because of their redistribution as the outer layers of metal are removed. Instances are known where residual stresses have caused structures to creep badly out of shape over a period of several years in service.

Stress relieving by heat treatment will practically remove residual stresses and prevent the above-mentioned difficulties. (See Chapter 43.) The value of and need for the relief of welding stresses is open to question but experience indicates that it is advantageous under certain conditions, such as: (1) structures subjected to dynamic loads, (2) structures which must accurately maintain their shape during their service life, (3) structures composed of heavy members and rigid joints which probably contain high residual stresses.

Tolerances for Machining

The process of welding is accompanied by a certain amount of shrinkage and distortion. In addition, rolled sections, plates, castings and formed parts are supplied with certain tolerances. In order that the finished product may meet the required dimensions it is essential that all of the above factors be taken into consideration.

Tolerances on rolled sections and formed parts are easily obtainable but it is impossible to give exact values to be allowed for distortion. The distortion obtained during welding is a function of the joint design, the amount of welding, the welding process, the position of welding, the fit-up of the parts and the use of fixtures, clamps, etc.

Tolerances on parts that are to be machined, based on many years of experience with fabricated machinery, are as follows:

1. Small parts containing very little welding—$^1/_8$ in.
2. Moderately large parts containing a small amount of welding—$^1/_4$ in.
3. Large structures containing moderate amounts of welding—$^3/_8$ in.
4. Large complicated structures and structures containing large amounts of welding—$^3/_8$ to $^1/_2$ in.

FABRICATION PROBLEMS

The economic advantages obtained from a welded structure are partly dependent upon the cost of fabrication. It is important, therefore, that considerable effort be spent in simplifying the manufacturing process, insuring that the welding is done properly and in eliminating unnecessary fit-up time and objectionable distortion.

Distortion

The importance of distortion depends largely upon the part being fabricated. In any case it is objectionable and often results in an undesirable straightening expense. The design and fabrication process should be worked out to reduce this trouble to a minimum.

The fact that distortion is the result of welding indicates that the amount of welding used should be held to the minimum that is consistent with the loads carried.

Excessive welding on one side of the neutral axis of a member will also produce undesirable distortion. Balancing the welding as well as possible is often desirable.

Properly tack welding the parts together or holding the assembly in place by clamps or fixtures will be helpful in maintaining the proper shape of the structure.

Poor fit-ups tend to produce excessive distortion.

In many cases distortion is compensated for by preforming the parts out of shape and permitting the deformation caused by welding to pull the structure back into the desired shape. Assembling the parts slightly oversize and permitting them to shrink to the desired size is often advantageous.

Use of Welding Fixtures

The use of welding fixtures to aid in the fabrication of welded machinery has many advantages. In general such fixtures are used for the following purposes:

1. Locate parts during assembly.
2. Hold parts in alignment during tacking and welding, thereby reducing distortion.
3. Position the structure to facilitate welding in any desired position.

Fixtures that are used primarily to prevent distortion must be more rigid than the structure itself, otherwise the fixture will distort and the desired result will not be obtained. To eliminate distortion of the structure when it is removed from the fixture the practice of stress relieving by heating the combined assembly before separation is sometimes used.

Preheating

Preheating machinery parts before welding is seldom done, except in special cases.

Parts made from special steels that will harden during welding should be preheated to insure sound welds and to reduce hard areas at the fusion line which might develop cracks or produce machining difficulties.

Structures made from heavy members are often preheated, even though the carbon content is low, because this treatment helps prevent weld cracks and aids in reducing distortion.

Fit-up Tolerances

Proper fit-up of all parts is essential in a structure. Wide gaps and poorly fitting members generally produce excessive distortion and require the deposition of excessive amounts of weld metal in order to make welds of the proper strength.

Fillet welded T-joints should be assembled so that metal-to-metal contact is obtained if possible. Except for designs requiring machining or some other specific means of insuring metal-to-metal contact or a very small reasonable gap a maximum tolerance of $^{3}/_{32}$ in. is often allowed for processing reasons. In special cases gaps up to one-half the thickness of the thinner member but not exceeding $^{3}/_{16}$ in. are allowed, provided means are taken to insure that the weld joint is equivalent in strength to that required by the design.

Fillet welded lap joints should have metal-to-metal contact if possible and the gap should not exceed $^{1}/_{8}$ in. unless the weld size is increased to compensate for this gap.

Corner joints should be assembled so that the gap between the butting corners does not exceed one-half the thickness of the thinner plates but in no case more than $^{1}/_{8}$ in.

Butt joints should be prepared and fitted up in accordance with the process specification governing the welding.

Joint Rigidity

Rigid joints are difficult to weld and may cause trouble from cracks resulting from the development of high residual stresses. Such joints should be avoided wherever possible, either by proper design or by the use of the proper welding procedure.

BIBLIOGRAPHY

1. *Development in Welding Large Structures,* C. C. Brinton, The Welding Journal, January 1938.

2. *Steel Plate Fabrication in the Heavy Machinery Field,* J. H. Cooper, The Welding Journal, February 1938.

3. *Designing Construction Machinery for Production by Welding,* H. C. Hettelsater, The Welding Journal, April 1940.

4. *The Fabrication of Large Equipment by Welding,* L. S. McPhee, The Welding Journal, April 1940.

5. *Welding Applications in Naval Machinery,* J. D. Bert and H. W. Hiemke, The Welding Journal, March 1942.

6. *Design of Welded Machinery,* J. Mikulak, The Welding Journal, January 1945.

7. *Trends in the Use of Welded Machinery Parts,* E. J. Charlton, The Welding Journal February 1945.

8. *Design Considerations for Welded Machinery Parts,* G. L. Snyder, The Welding Journal, February 1946.

9. *Welding a 600 H. P. Diesel Engine,* L. Berner, The Welding Journal, April 1946.

10. *Evolution of Diesel Engine Block Weldment Design and Fabrication,* J. W. Owens, The Welding Journal, March 1947.

11. *Development of Jacketed-Type Steel Drier Rolls,* W. H. Funk, The Welding Journal, April 1947.

12. *Welding in Machine Design,* J. Mikulak, The Welding Journal, April 1948.

CHAPTER 50

FIELD-WELDED STORAGE TANKS*

INTRODUCTION

Use of Storage Tanks

THE GROWTH OF our cities and towns has increased the demand for water storage and the increased use of automobiles and of oil for heating has increased the requirements for oil storage. These, with other industrial requirements, have developed a great demand for large field-constructed storage tanks.

General Characteristics

This discussion of field-welded storage tanks will be confined to bulk storage tanks too large for shop assembly, necessitating field erection. Such tanks have diameters greater than 12 ft. and are generally erected vertically. By this is meant cylindrical steel tanks with vertical axes, designed to contain liquid products, operating generally at atmospheric pressure or at not over 15 psi. gage pressure. This includes oil storage tanks of various types, standpipes, reservoirs and elevated tanks for the storage of water and tanks for storing miscellaneous liquid and industrial products.

It is understood, of course, that the gage pressure on any tank is measured above the liquid level.

Governing Codes and Specifications

Field-welded storage tanks are usually constructed in accordance with some code or specification prepared for a particular industry.

The AMERICAN WELDING SOCIETY *Standard Rules for Field Welding of Steel Storage Tanks* (D5.1) provides complete specifications for the construction of storage tanks for all types of service except that no unit stresses for the steel plating are specified. These unit stresses will depend upon the service conditions involved and may be found in the industrial specifications listed in the bibliography at the end of this chapter.

MATERIALS

Steels containing a low carbon and manganese content, commensurate with the required physical properties, will usually be better for welded construction than those containing a high carbon and manganese content.

Field-welded storage tanks are usually constructed of one of the following materials:

Plates.—Open-hearth plate materials conforming to any of the following American Society for Testing Materials Specifications:

A7 Steel for Bridges and Buildings.
A283 Low and Intermediate Tensile Strength Carbon-Steel Plates of Structural Quality. (all grades.)
A285 Low and Intermediate Tensile Strength Carbon-Steel Plates of Flange and Firebox Qualities.
A113 Structural Steel for Locomotives and Cars (Grade C, Cold Pressing Plates).

Structural.—Open-hearth structural materials conforming to either of the following American Society for Testing Materials Specifications:

A7 Steel for Bridges and Building.
A113 Structural Steel for Locomotives and Cars.

Copper-Bearing Steel.—Copper-bearing steel with a copper content of about 0.20% will resist atmospheric corrosion a

* Prepared by a committee consisting of H. O. Hill, Bethlehem Steel Co., *Chairman;* H. C. Boardman, Chicago Bridge & Iron Co.; J. B. Fullman, A. M. Byers Co.; J. O. Jackson, Pittsburgh-Des Moines Steel Co.; F. L. Plummer, Hammond Iron Works; M. V. Reed, Dallas Tank Co., Inc.; T. D. Tifft, Sinclair Refining Co.

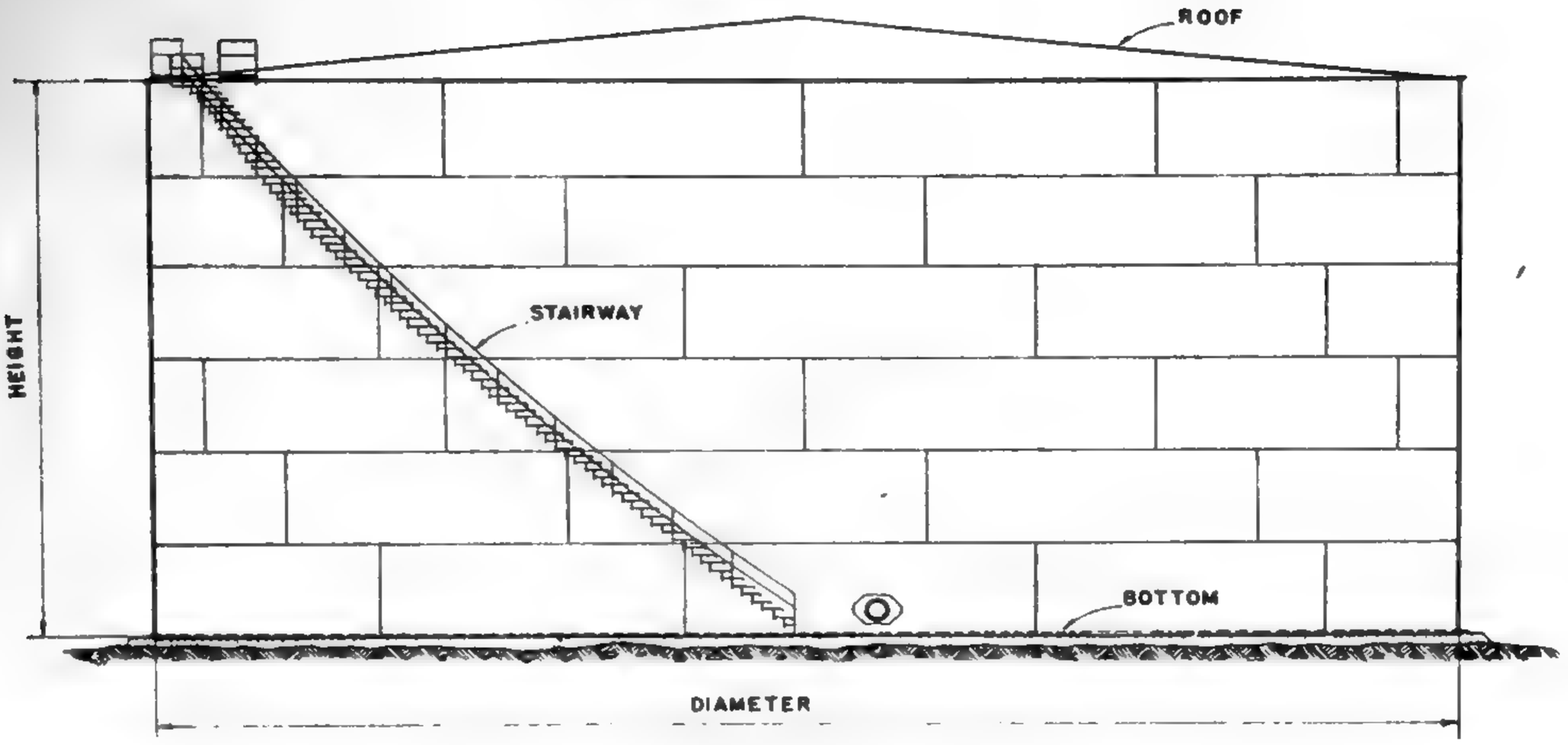


Fig. 1.—Cylindrical Oil Storage Tank with Cone Roof

little better than plain-carbon steels; for that reason such a copper content is sometimes specified for the above-mentioned steels.

Electrodes.—Arc-welding electrodes are usually specified to conform to the requirements of the AWS-ASTM *Specifications for Mild Steel Arc-Welding Electrodes* (AWS Designation A5.1; ASTM Designation A233), using any of the following grades: E6010, E6011, E6012, E6013, E6015, E6016, E6020 and E6030, depending upon the position of welding and other conditions of intended use (see Chapter 38 for a description of these electrodes).

DESIGN

Types of Tanks

The most common shape of storage tank is the vertical tank with a cone roof and flat bottom. Figures 1 to 12 show the more common types. The need for preventing excessive evaporation losses of volatile oils has led to the development of special types of oil-storage tanks differing in various details. Also in the case of

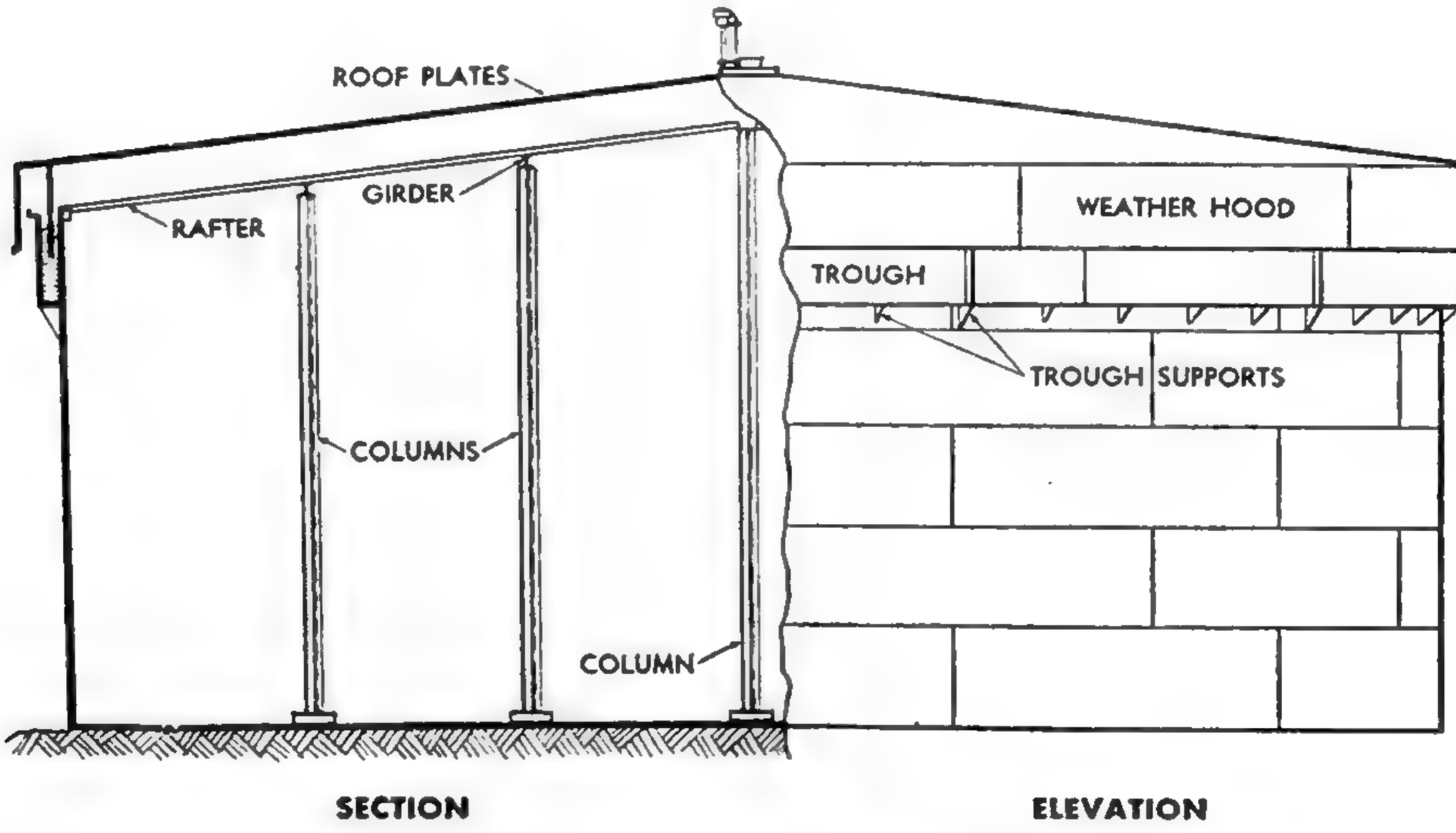


Fig. 2.—Oil Storage Tank with Lifter Roof

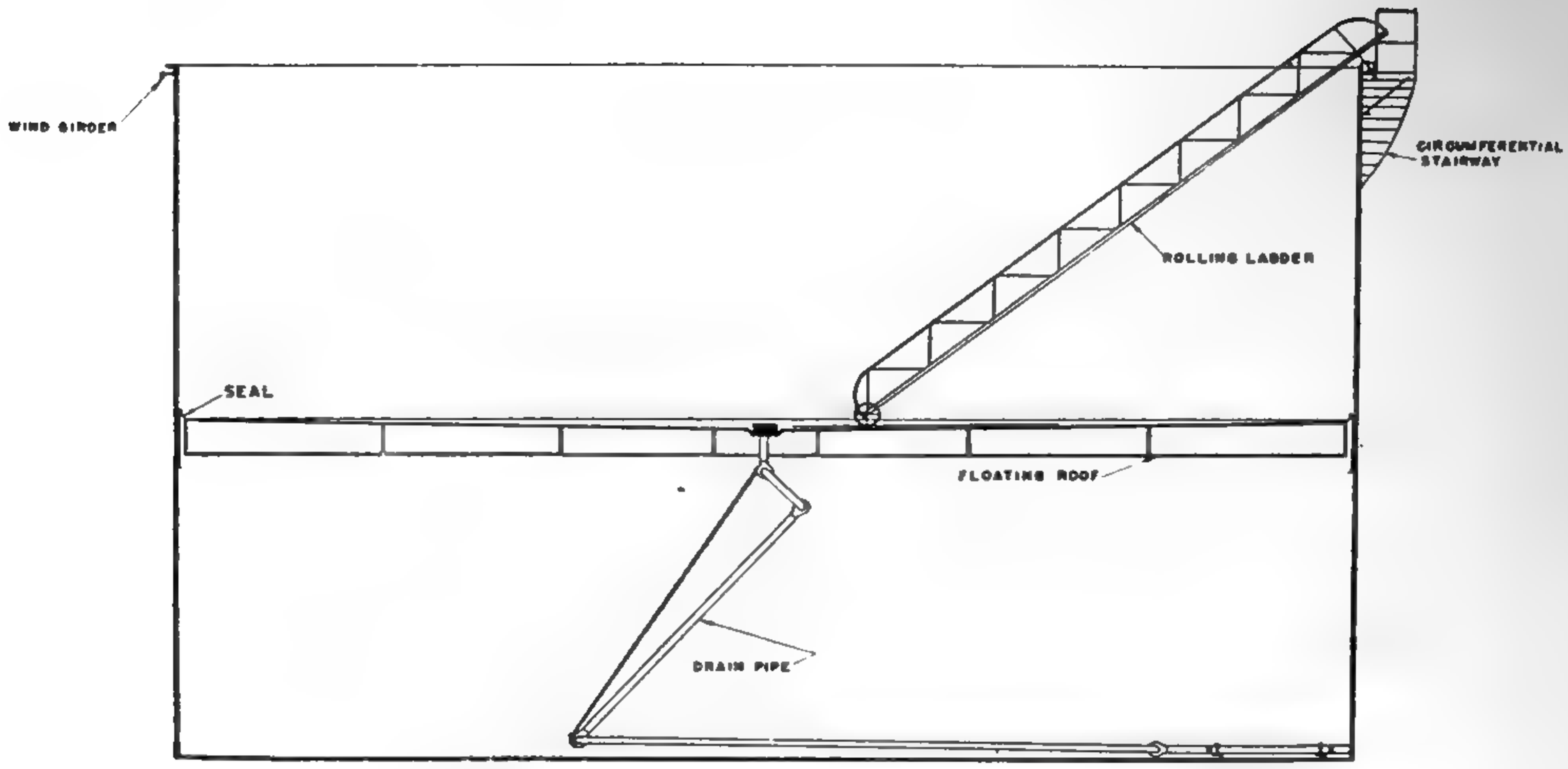


Fig. 3.—Oil Storage Tank with Floating Roof

water-storage tanks it is sometimes necessary to elevate the tank on a tower in order to obtain a suitable gravity head for distribution purposes. The more common types are as follows:

1. *Cylindrical storage tank with cone roof and flat bottom.* This type is used for general bulk storage of oil products, tar, alcohol and miscellaneous industrial liquids. (See Fig. 1.)

2. *Oil-storage tank with lifter roof,* the roof of which elevates to increase the vapor space and prevent the loss of vapors during the warm period of the day. It does not conserve vapors during filling or emptying operations but is suitable for standing storage of gasoline and other volatile products. (See Fig. 2.)

3. *Oil-storage tank with floating roof.* The roof floats upon the liquid and insulates the surface of the liquid and reduces vapor losses. These roofs conserve vapors during filling and emptying of the tank but are not as tight against

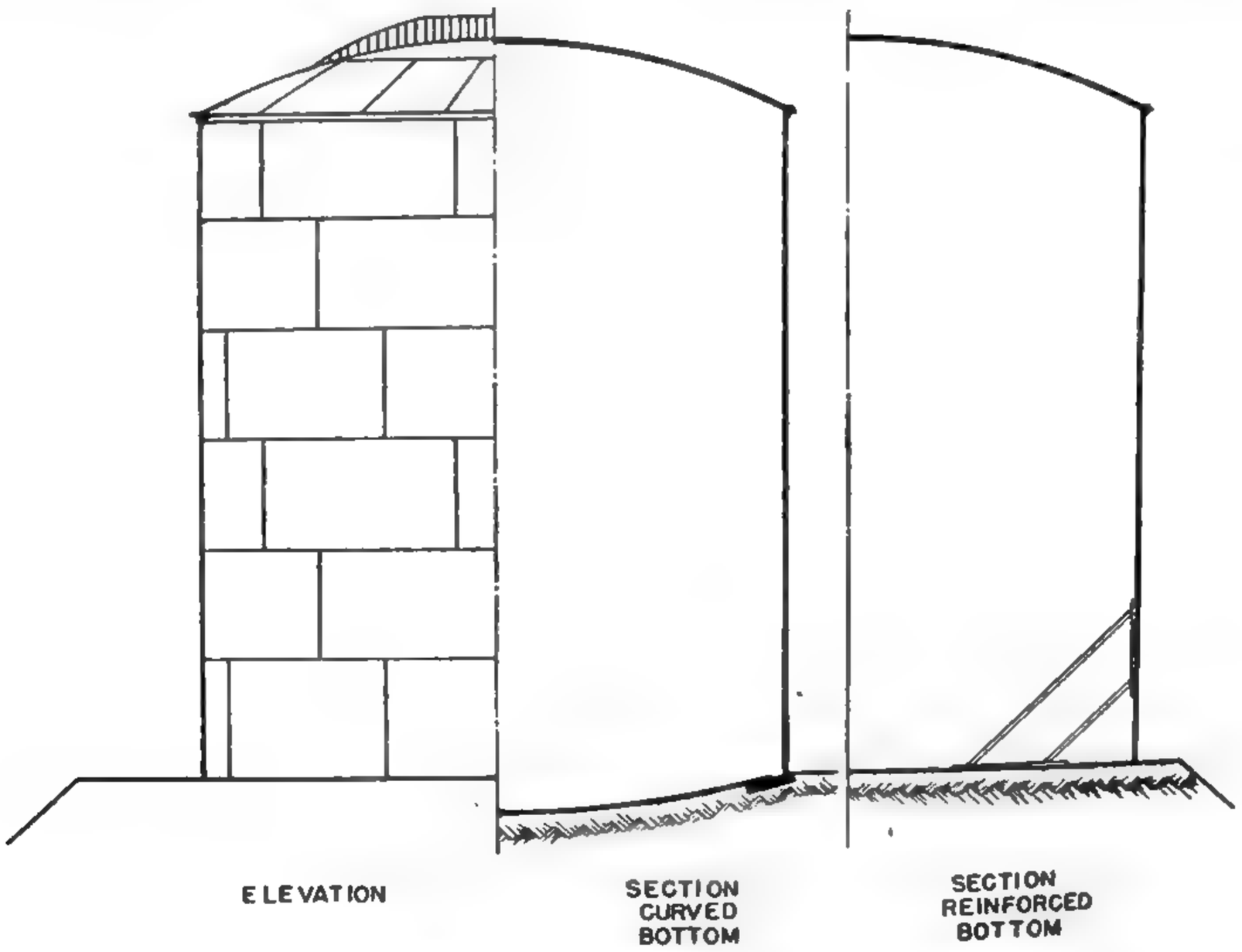


Fig. 4.—Dome Roof Tanks with Curved and Flat Reinforced Bottom

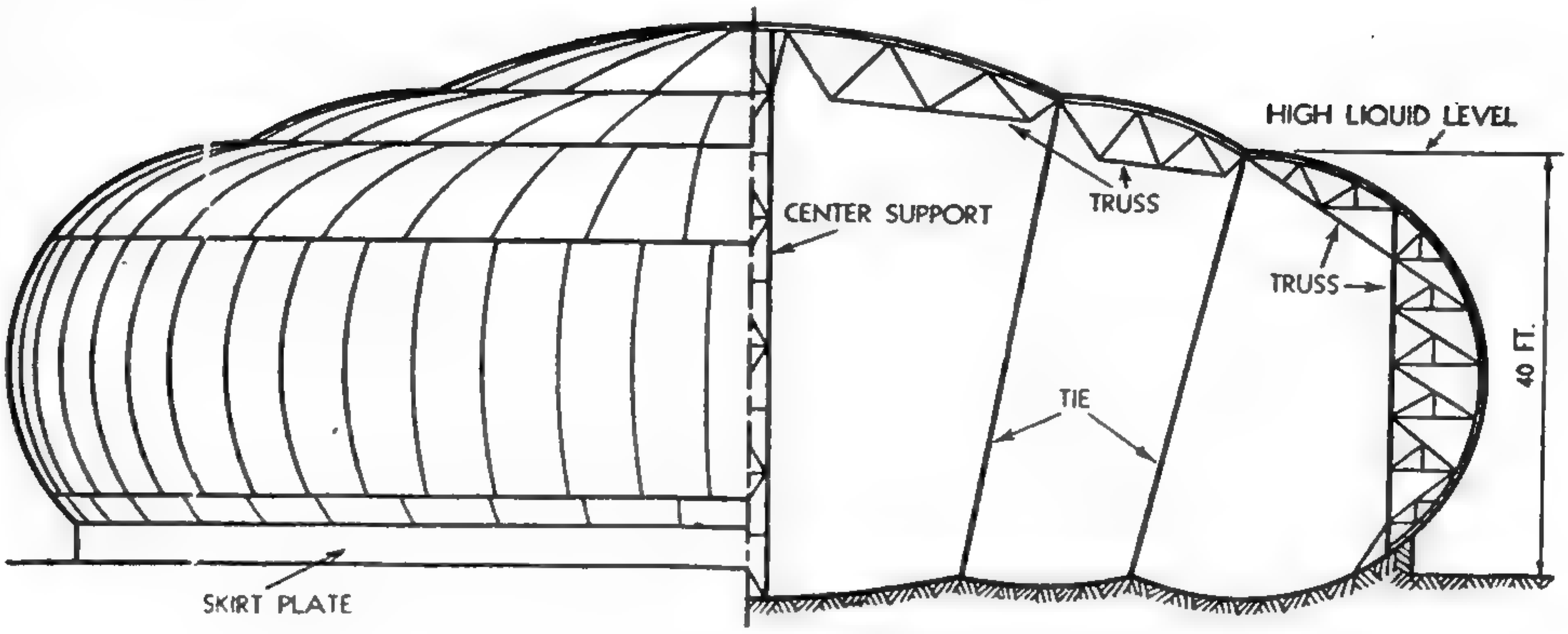


Fig. 5.—Noded Spheroid for Storing Products Under Low Pressure

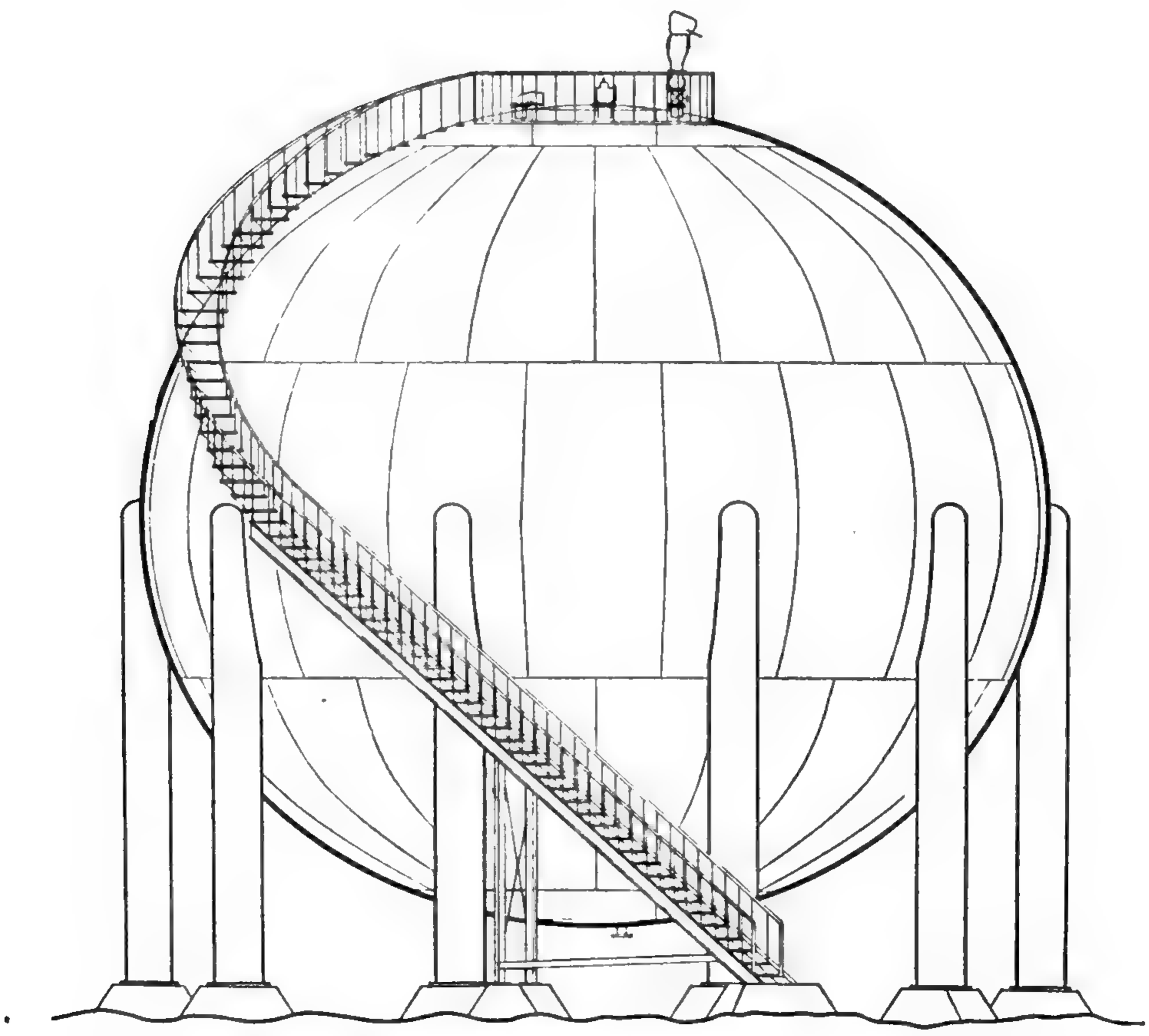


Fig. 6.—Sphere for Storing Gas or Petroleum Products Under Pressure

vapor loss as lifter roofs for standing storage. They are very serviceable for active storage of gasoline or other volatile products. (See Fig. 3.)

4. *Domed-roof tank with flat reinforced bottom or with curved bottom.* These are usually used for storing petroleum products under low pressure to prevent evaporation. (See Fig. 4.)

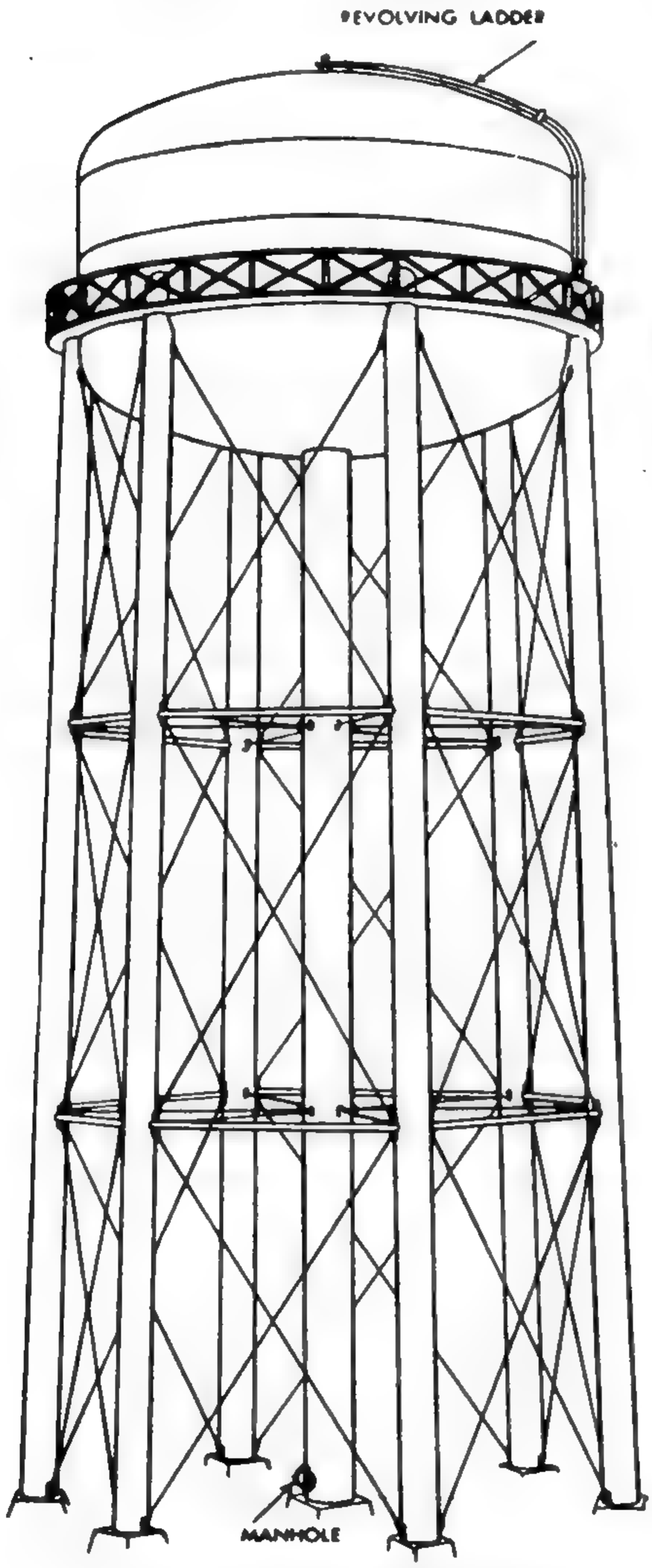


Fig. 7.—Elevated Water Storage Tank

5. *Spheroid for storing petroleum products under low pressure,* not exceeding 15 psi., which permits a pressure above atmospheric to be applied to the surface of the liquid with nearly uniform stresses throughout the shell. These vessels may be plain or noded. (See Fig. 5 for noded spheroid.)

6. *Sphere for storing gas or petroleum products under pressure,* which permits a pressure above atmospheric with nearly uniform stresses throughout the shell. Such tanks are frequently built for a pressure range above 15 psi. gage pressure and in such a case they become pressure vessels and should be constructed under the ASME *Unfired Pressure Vessel Code* or the API-ASME *Code for Unfired Pressure Vessels for Petroleum Liquids and Gases.* (See Fig. 6.)

7. *Elevated water-storage tank,* used to store water and by elevation to provide sufficient pressure for water-distribution systems or for fire protection. (See Fig. 7.)

8. *Cylindrical water standpipe with domed roof.* This tank is used for bulk storage of water for domestic service. Pressure is obtained by locating the tank on ground elevations or by pumping. The domed roof is solely for ornamental purposes. (See Fig. 8.)

9. *Cylindrical water standpipe with conical roof.* This tank is used for bulk storage of water for domestic service. Pressure is obtained by locating the tank on ground elevations or by pumping. (See Fig. 9.)

10. *Process tank with cylindrical shell, elliptical roof and conical bottom on structural supports.* This tank is used in many industrial plants for storing and handling liquids or dry products during manufacture. (See Fig. 10.)

11. *Underground storage tank.* This tank is usually used for storing finished petroleum products. It is used chiefly where tanks located above ground would be objectionable due to zoning requirements or for military purposes. (See Fig. 11.)

12. *Railroad water tank.* This tank is used by railroads for storing water for locomotive service. (See Fig. 12.)

Each type of tank requires its special accessories such as foundations, vents, gages, drains, overflows, manholes, etc., depending upon the proposed content, local conditions and regulations. The design, construction and application of these

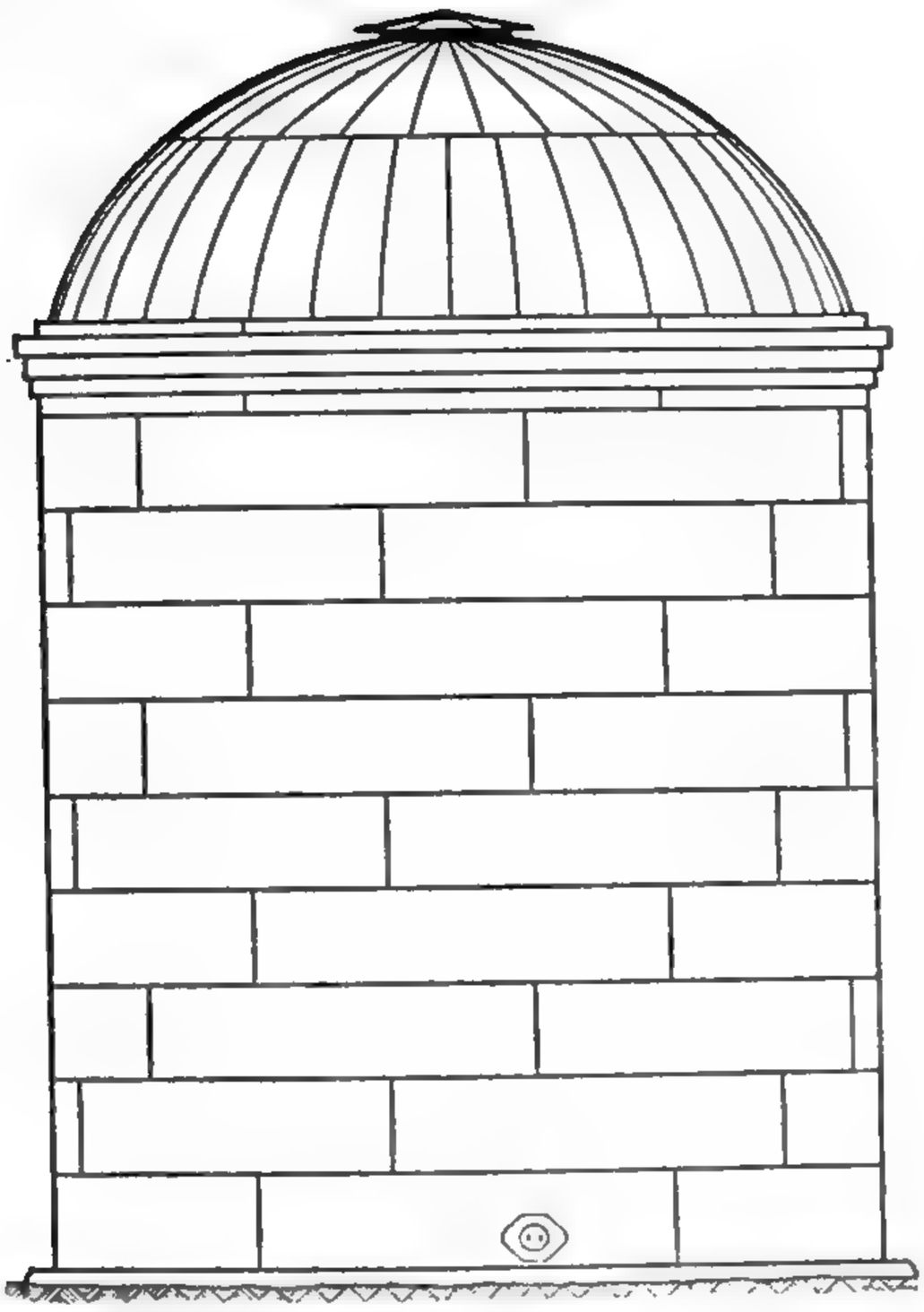


Fig. 8.—Cylindrical Water Standpipe with Dome Roof

accessories should be handled by men of experience in this field.

Unit Stresses

Steel Plates.—Industry usually specifies the unit stress requirements for the steel plating to be used in the construction of storage tanks. This varies from about 15,000 psi. for water-storage tanks to 21,000 psi. for tanks containing petroleum products, depending upon the service requirements. The specifications mentioned in the bibliography should be referred to for unit stresses.

Welds.—Butt joints welded from both sides with complete penetration and double, full-fillet-welded lap joints will usually show 100% strength values when

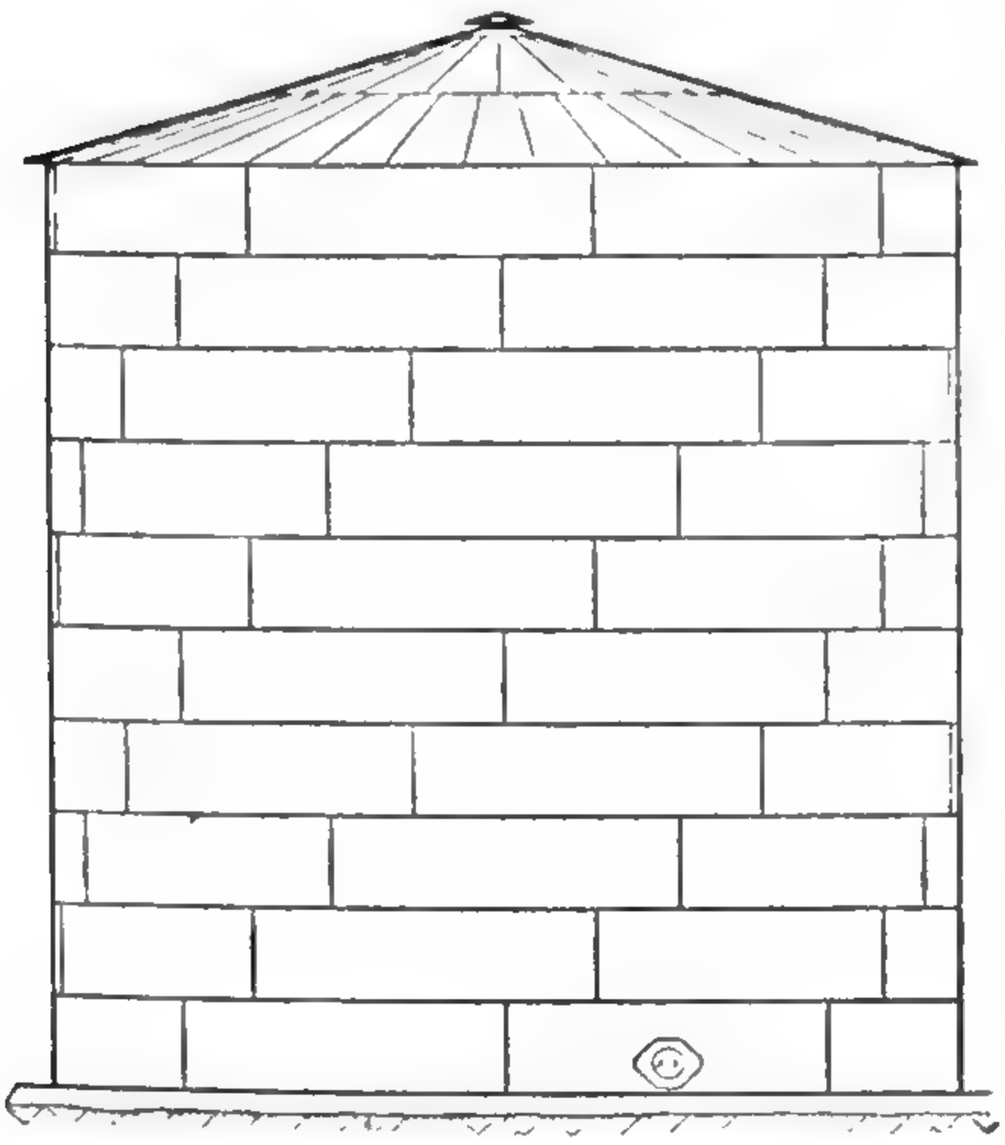


Fig. 9.—Cylindrical Water Standpipes with Conical Roof

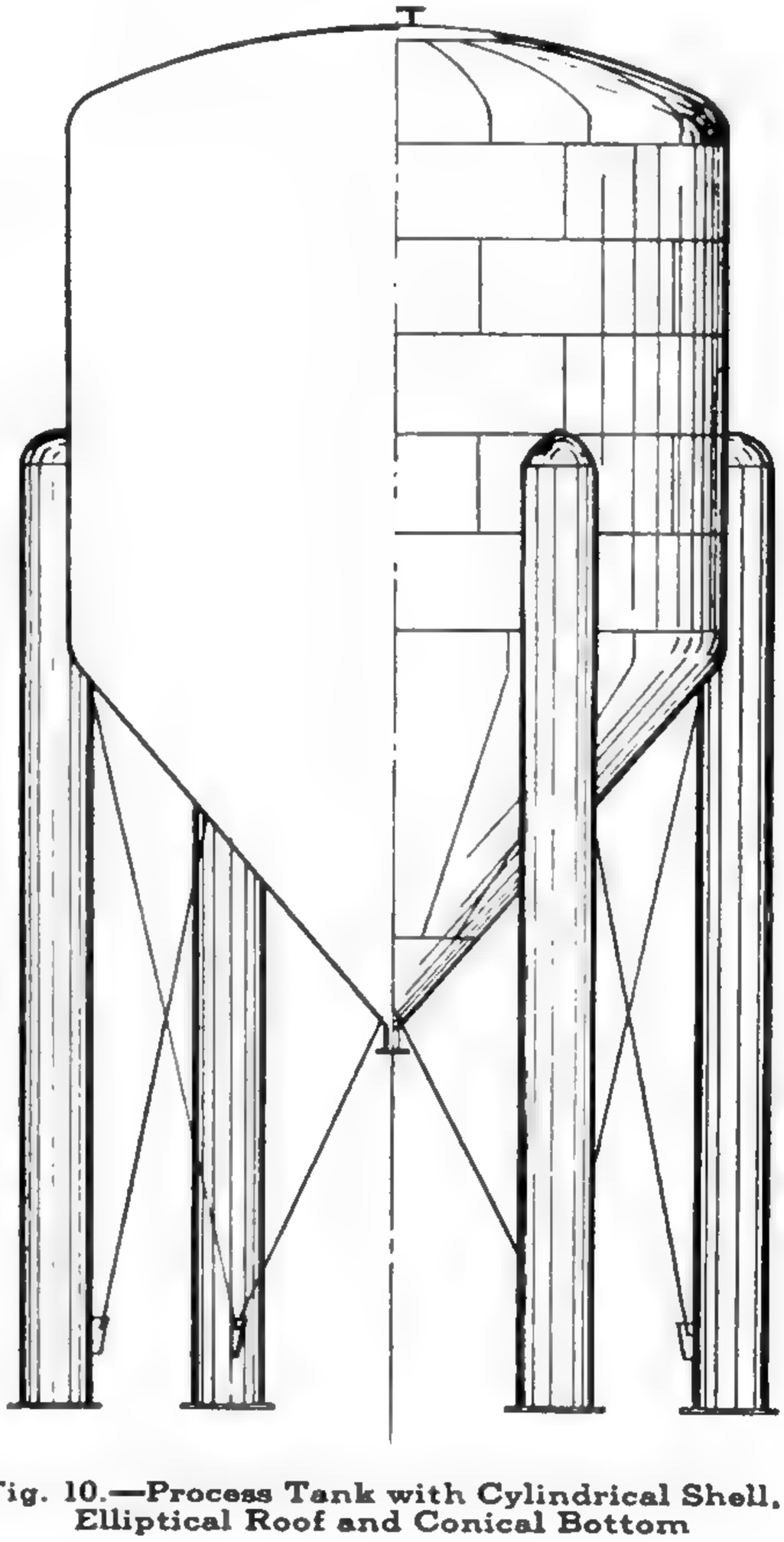


Fig. 10.—Process Tank with Cylindrical Shell, Elliptical Roof and Conical Bottom

tested with the usual narrow test coupons. Wide, unwelded plates, and wide welded plates will show lower tensile values than narrow test coupons. It is therefore advisable to assign efficiency values for welded joints to provide for the foregoing condition and also for deficiencies in the welded joints.

The following weld design values are usually used in the design of field-welded storage tanks:

Butt joints welded from both sides in tank shell plating, 85% efficiency, based upon the unit stress used for the plate material.

Double, full-fillet-welded lap joints in tank shell plating, 75% efficiency, based upon the unit stress used for the plate material.

with an unwelded portion, not over one-third the thickness of the plate, located substantially at the center of the joint. If single-vee groove welds are used, it is customary to require complete penetration.

The joint connecting the shell to the bottom on vertical cylindrical tanks is usually made with a continuous fillet weld on both sides of the shell plate of size equal to thickness of the bottom plate or

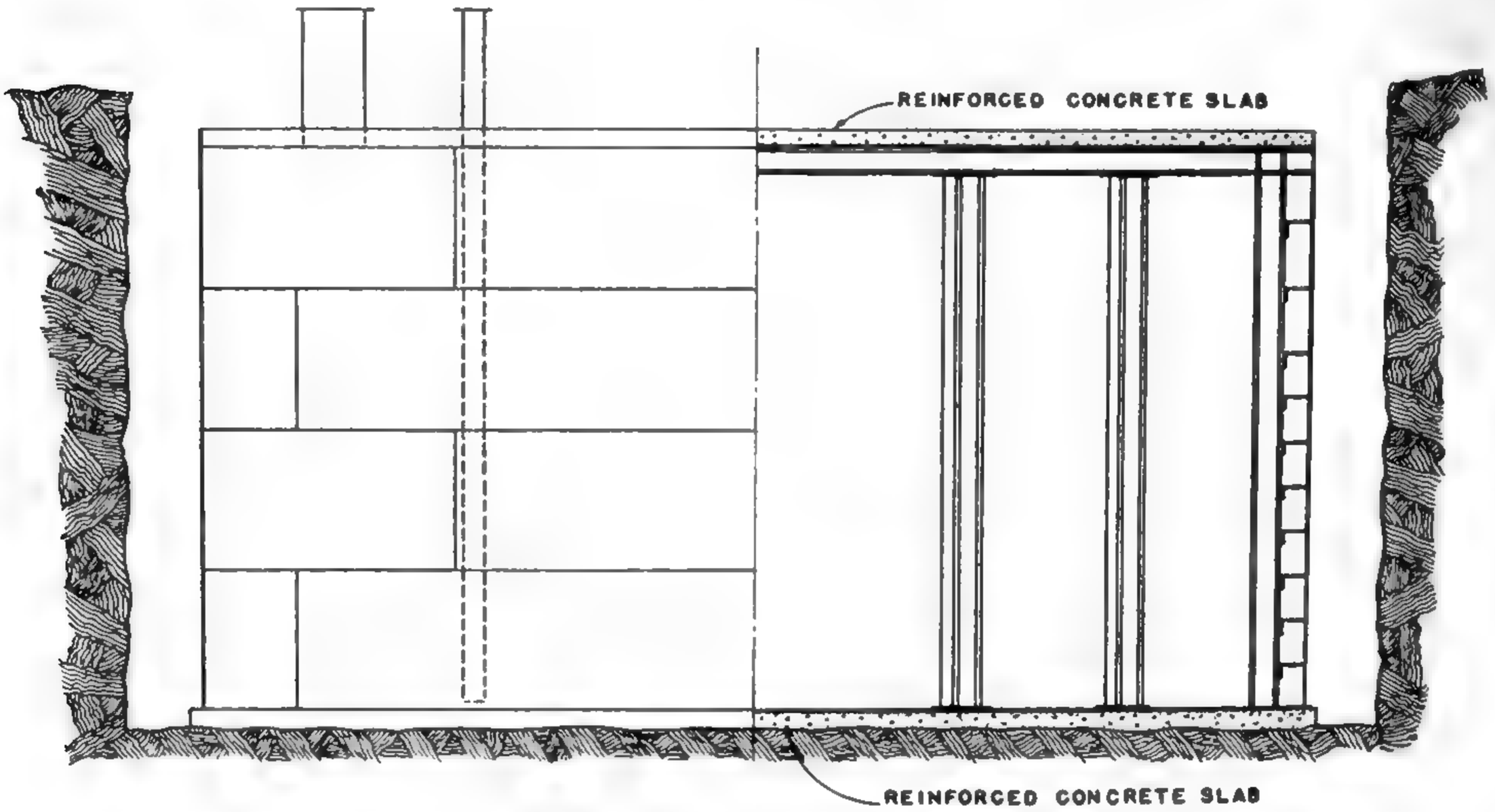


Fig. 11.—Underground Storage Tank

Typical Welding Details

The plate seams which resist primary stress from the weight or pressure of tank contents require welded joints of high strength. These are the vertical joints in cylindrical tank shells, joints below the point of support in tanks with suspended bottoms and all the joints in low-pressure tanks. These joints should be welded to obtain complete penetration and fusion throughout the thickness of the material. They are usually welded from both sides using square groove welds for material $^{5}/_{16}$ in. thick and thinner and double-vee groove welds for heavier material.

Seams subject to secondary stress, such as the circumferential seams of cylindrical tank shells, do not require full strength joints. They are usually welded from both sides to obtain at least two-thirds complete penetration, half from each side, the shell plate, whichever is smaller with a maximum size of $^{1}/_{2}$ inch.

Bottom and roof plates on vertical cylindrical tanks, if the thickness does not exceed $^{1}/_{2}$ in., are usually connected with fillet welds applied to the top side only. Heavier plates are usually groove-welded.

Typical welding details for a field-erected tank constructed with butt-welded shell are shown in Fig. 13.

WORKMANSHIP

Welder and Procedure Qualification

In order to insure that the welding will be properly performed, it is necessary to arrange to have all welders properly qualified and also to have the welding procedure that will be used in the welding of each type of joint, in each position of welding, properly qualified. The qualification should be performed according to

the requirements of the AWS *Standard Qualification Procedure* which will be found in Chapter 60.

Surface Preparation

Surfaces to be welded should be free from loose scale, slag, heavy rust, grease, paint and any other foreign material excepting tightly adherent mill scale. A light film of linseed oil or spatter film compound may be disregarded. Such surfaces should also be smooth, uniform and free from fins, tears, and other defects which adversely affect proper welding. A fine film of rust adhering on cut or sheared edges after wire-brushing need not be removed.

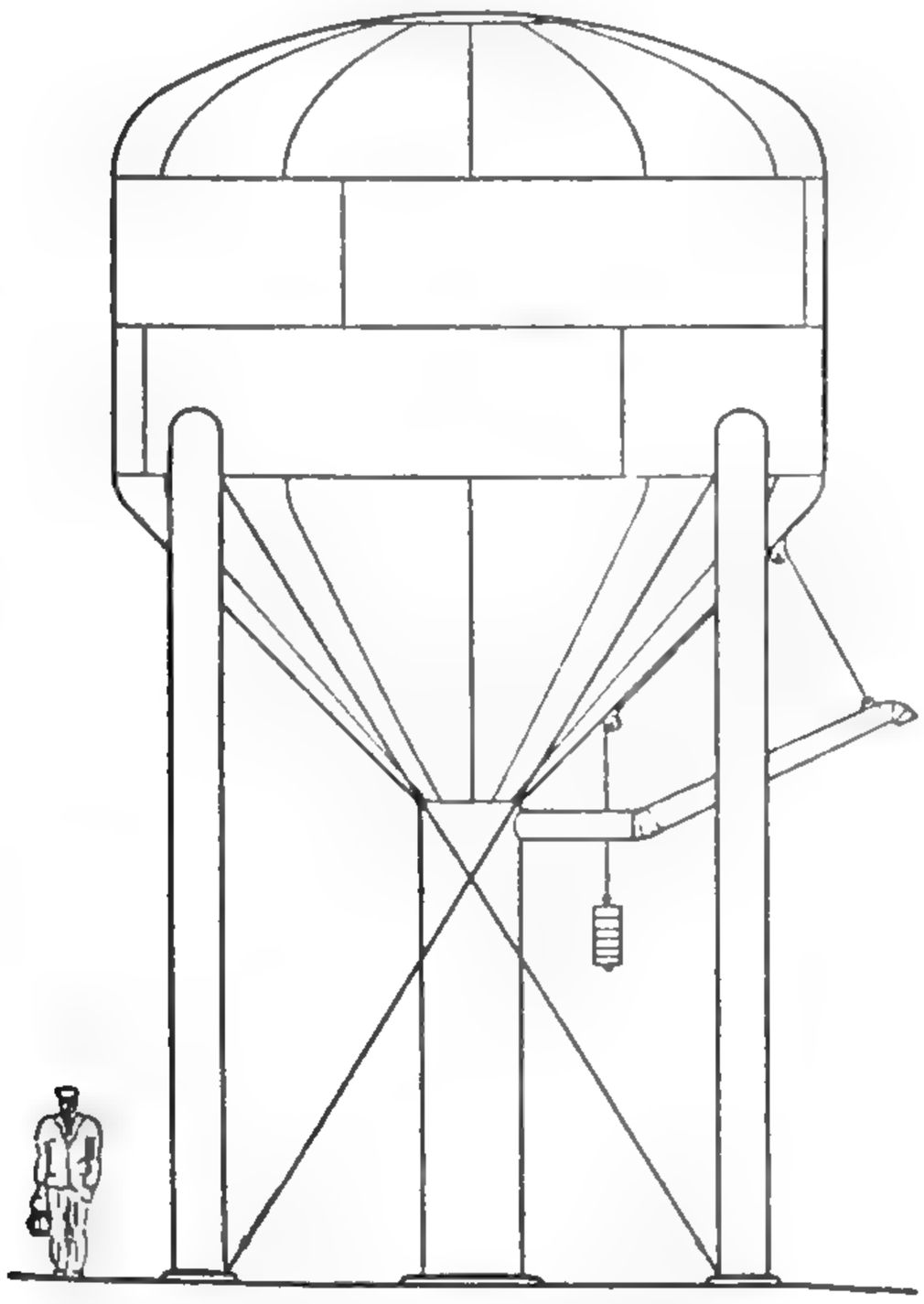


Fig. 12.—Railroad Water Tank

Weather Conditions

Welding should not be performed when the temperature of the base metal is below 0°F.; when surfaces are wet from condensation, rain, snow or ice; when rain or snow is falling on the surfaces to be welded; nor during periods of high wind unless the welder and the welding setup are properly protected. At temperatures between 32 and 0°F., the surfaces of all areas within 3 in. of the point where the weld is to be started should be heated to a temperature warm to the hand before the welding is started.

Cleaning Between Beads

Each bead of a multiple-layer weld should be cleaned of slag and other loose deposits before applying the next bead.

Chipping and Oxygen Gouging of Weld

Chipping of the roots of welds to remove defects should be performed with a round-nosed tool or by oxygen gouging.

INSPECTION AND TESTING

Inspection

It is advisable to have an experienced inspector who will intelligently check all construction details. This inspector should not be responsible to, or in the employ of, the superintendent or foreman in charge of construction. He should be given full authority to insist upon compliance with the applicable codes or specifications.

The purchaser may, if he so desires, have the steel inspected at the rolling mills and have the fabrication inspected in the fabricating shop in order to have assurance that materials and workmanship comply with the prescribed specifications.

Field inspection of the erection may also be performed if desired. The important welded joints should be checked by sectioning methods as mentioned in the succeeding paragraph.

Testing

Sectioning.—Tank shells may be tested by sectioning methods as prescribed in Section VIII of the AMERICAN WELDING SOCIETY *Rules for Field Welding of Steel Storage Tanks.*

Flat Tank Bottoms.—Joints in tank bottoms resting on grades or foundations may be tested by the magnetic-particle method, or by coating the joints with a suitable material such as strong soap solution or linseed oil and then applying air pressure or vacuum, which will disclose leaks by the appearance of bubbles. Flat tank bottoms may be tested by first attaching the lowest shell course and then pumping water underneath the bottom and maintaining a head of at least 6 in. of liquid by holding that depth around the edge of the bottom, inside a temporary dam.

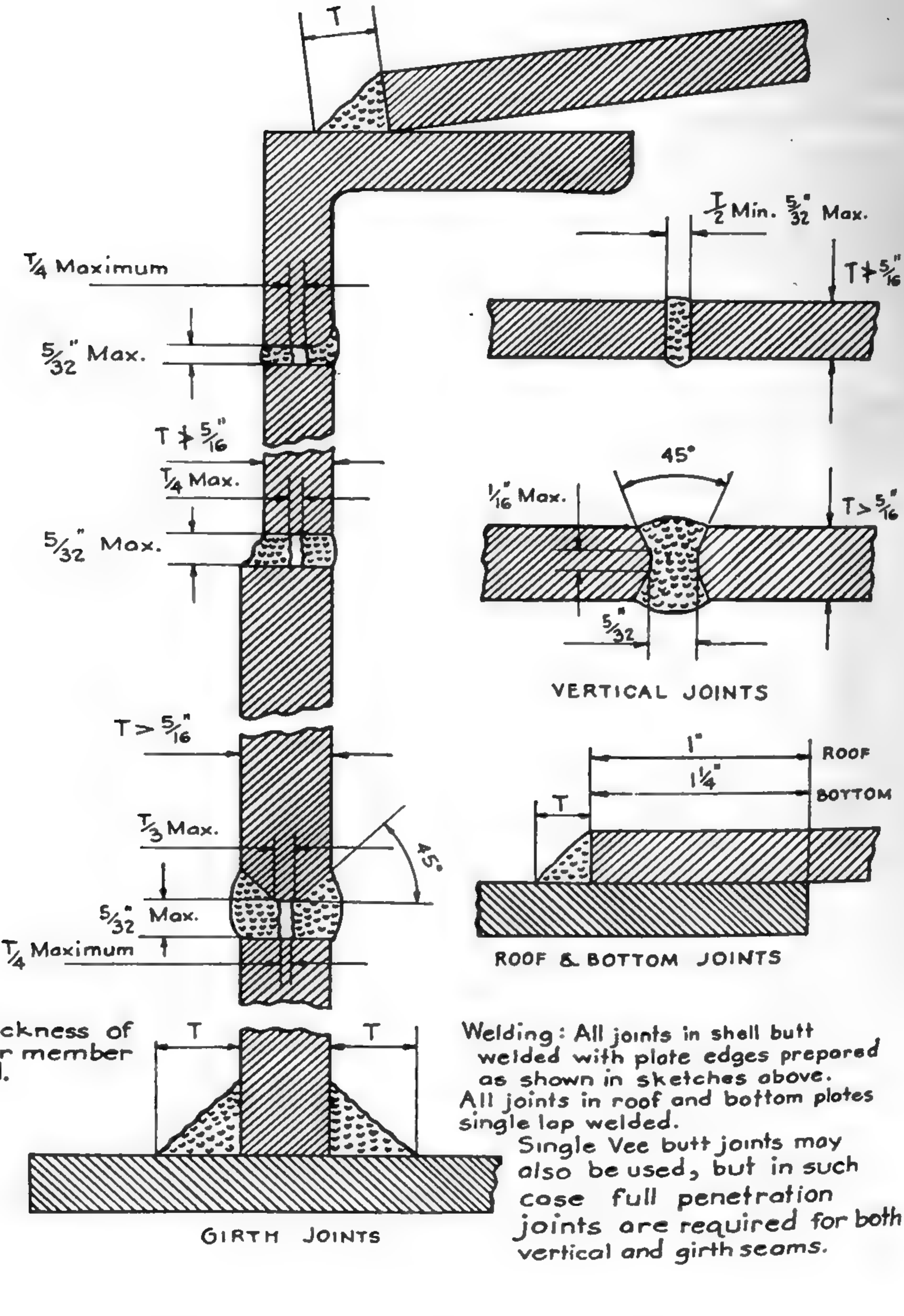


Fig. 13.—Typical Welding Details, Tank with Butt-Welded Shell

Finally, whenever possible, the entire storage tank should be tested by filling with water.

All leaks discovered should be repaired.

The weldability of wrought iron and welding procedure for wrought iron are discussed in Chapter 27.

Materials.—When wrought iron is specified it shall conform to the latest revision of the following specifications of the American Society for Testing Materials:

A42	Wrought Iron Plates.
A72	Welded Wrought Iron Pipe.
A162	Uncoated Wrought Iron Sheets.
A163	Zinc-Coated (Galvanized) Wrought Iron Sheets.
A189	Single and Double Refined Wrought Iron Bars.
A207	Rolled Wrought Iron Shapes and Bars.

Filler metals suitable for use with wrought iron are discussed in Chapter 38.

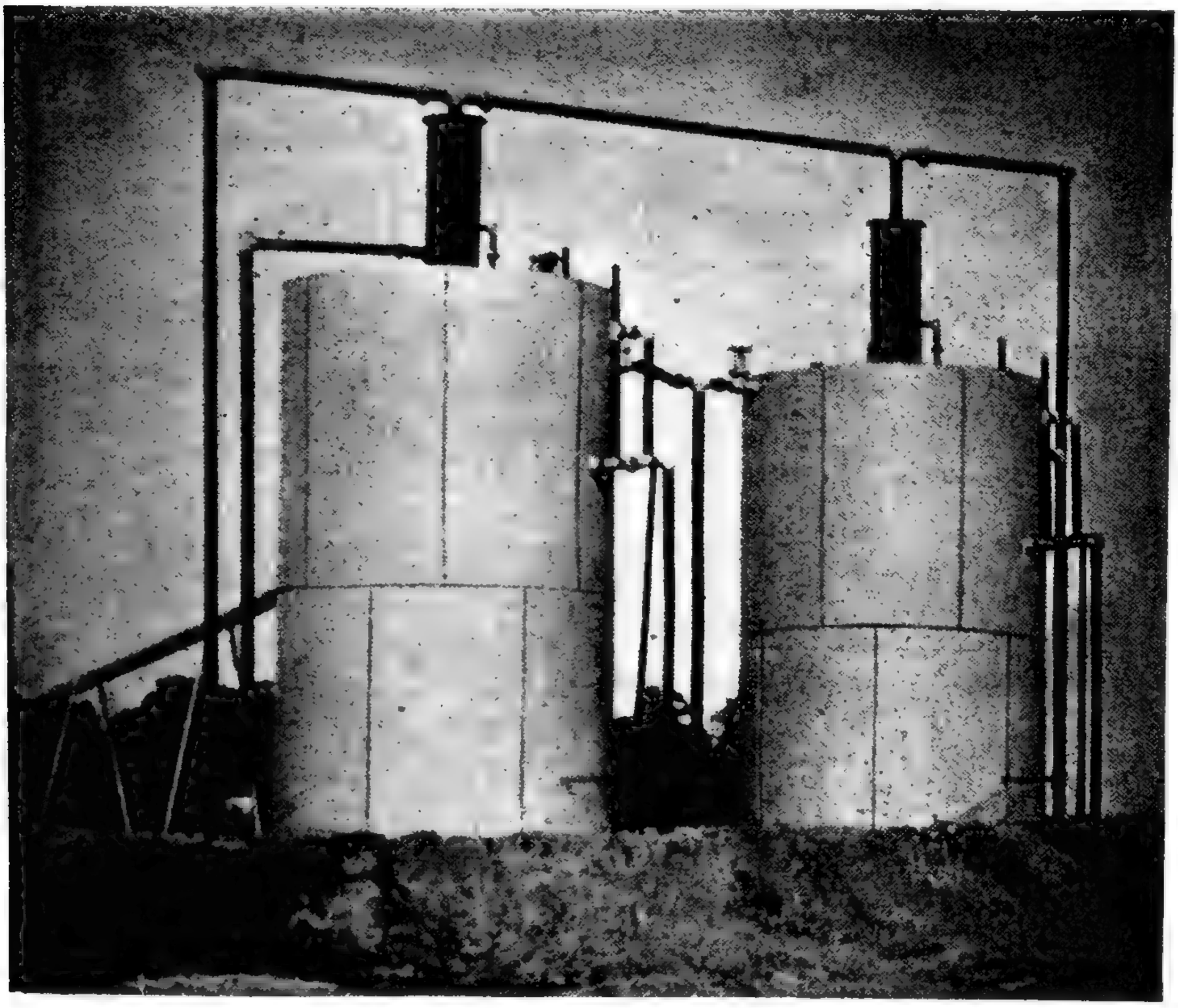


Fig. 14.—Welded Wrought-Iron Treating Tanks

WROUGHT IRON STORAGE TANKS

In the section of this chapter dealing with steel tanks the AMERICAN WELDING SOCIETY *Standard Rules for Field Welding of Steel Storage Tanks* are cited. Thus far no officially adopted rules for field welding of wrought-iron storage tanks have been prepared. Practical experience has demonstrated wrought iron's suitability for tank construction and it has been used satisfactorily for handling fresh water, oil, salt water, caustic soda, animal fats and a wide variety of other corrosive substances. Figure 14 illustrates a typical installation.

BIBLIOGRAPHY

1. *Specifications for Gravity Water-Tanks and Steel Towers,* Associated Factory Mutual Fire Insurance Companies, 1938.

2. *Standards for the Construction and Installation of Tanks, Gravity and Pressure, Towers, Etc.,* National Board of Fire Underwriters, 1941.

3. *Standard Rules for Field-Welding of Steel Storage Tanks,* D5.1, American Welding Society, 1947.

4. *Specifications for All-Welded Oil Storage Tanks,* 12-C, American Petroleum Institute, September 1948.

5. *Standard Specifications for Elevated Steel Water Tanks, Standpipes and Reservoirs,* (7H.1; D 5.2), American Water Works Association-American Welding Society, 1948.

6. *Specifications for All-Welded Steel Tanks for Railway Water Service,* American Railway Engineering Association.

7. *The Application of Welding to Large Steel Tanks,* H. C. Boardman, The Welding Journal, June 1937.

8. *Welding Aids in the Construction of Large Storage Tanks,* T. D. Tifft, The Welding Journal, August 1938.

9. *Large Welded Elevated Water Tanks,* H. C. Boardman, The Welding Journal, March 1939.

10. *Welded Liquefied Natural Gas Storage Tanks,* J. O. Jackson, The Welding Journal, December 1941.

11. *Field Welded Pressure and Variable Volume Storage Tanks,* F. L. Plummer, The Welding Journal, January 1945.

CHAPTER 51

PRESSURE VESSELS AND BOILERS*

INTRODUCTION

Scope

THIS CHAPTER deals with closed end vessels which are subjected to internal or external pressure, both fired and unfired, as used in the various industries.

Pressure Vessel Classification

A vessel is defined as a pressure vessel for administrative purposes if the maximum working pressure exceeds 15 psi. and the size exceeds certain limits (see Table 3). Such vessels are generally cylindrical shells with ellipsoidal or conical ends, or spheres, or combinations of any surfaces of revolution. It is sometimes difficult to classify a particular piece of equipment as a *pressure vessel* or as *piping*, particularly with the general trend toward larger sized units with attendant increase in the size of the piping. Pressure equipment used to transport the process medium from one vessel to another is generally classified as piping, regardless of size. Individual manufacturers often apply pressure vessel design and fabrication practice to large piping and to large, low-pressure vessels.

Boilers and Unfired Vessels

Steam boilers are, as a class, operated at lower maximum temperatures than many pressure vessels used in the oil refining and chemical industries. The steam and water drum of a boiler may be heated to the temperature of saturated steam (approximately 700°F. maximum, but generally much lower depending upon the operating pressure) whereas an unfired pressure vessel in one of the process industries may be subjected in service to a temperature as high as 1200°F. with applications in the 800 to 1000°F. range quite numerous. Steam superheaters are operating at 1400°F. and are being designed for considerably higher temperatures.

The drums of power boilers and superheaters are generally, but not always, exposed to furnace gases and sometimes also to radiation with attendant high rates of heat transfer. They are therefore considered *fired*. The great majority of vessels in other industries are not similarly exposed and are classified as *unfired* vessels.

Construction Methods and Development of Welding

Welding, as applied to pressure vessel construction, gained initial impetus with the simultaneous development of heavy covered electrodes and industrial radiographic equipment and the adoption in 1930 of rules by code-making bodies and authorities and has made rapid strides to its current universally accepted position. Rapid developments during the past two decades in the boiler, chemical and petroleum industries utilizing increasingly higher pressures, higher temperatures, new materials and large-scale units have furthered the development of the welding processes.

As a matter of interest, the four types of pressure vessel construction which have supplied industrial demands over the past years are compared in Table 1. At the present time, forge welding has practically disappeared and riveting no longer occupies the status of active competition, being used only for special production items where highly developed or existing manufacturing equipment results in low cost or where local regulations still favor this construction. In the railway locomotive field, welded construction

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Table 1—Comparison of Types of Pressure-Vessel Construction

CONSTRUCTION		ARC WELDED	FORGE WELDED	RIVETED	SEAMLESS FORGED
MAXIMUM THICKNESS		AT LEAST 6 IN – GREATER THICKNESSES PRACTICAL WITH LAYER CONST.	2 3/8 IN.	2 3/4 IN.	LIMITED BY VESSEL SIZE & INGOT WEIGHT
MAXIMUM DIAMETER		UNLIMITED	UNLIMITED	UNLIMITED	LIMITED BY PRESSURE SIZE
THICKNESS		UNLIMITED	1/4 IN MINIMUM	3/16 IN. (CAULKED SEAMS) MINIMUM	APPLICABLE ONLY TO RELATIVELY THICK WALL VESSELS
MAX. JOINT EFFICIENCY	ASME CODE	95 %	88.6 %	93 % FOR 1 IN, LESS FOR GREATER THICKNESSES	100 %
	API–ASME CODE	95 %	75.0 %		
COST		COMPARATIVELY ECONOMICAL	MORE EXPENSIVE	COMPARATIVELY EXPENSIVE	RELATIVELY EXPENSIVE
WEIGHT	MATERIAL	SHELL & WELD ROD	SHELL AND LAPS	SHELL PLUS LAPS, BUTT STRAPS & RIVETS	EXCESSIVE DUE TO FORGING TOLERANCES,
	FINISHED VESSEL	NO EXCESS	NO EXCESS	EXTRA WEIGHT – BUTT STRAPS, LAPS & RIVETS	OFTEN MACHINED TO THICKNESS
MATERIALS		ANY WELDABLE MATERIAL	LIMITED TO READILY WELDABLE MATERIAL WITH LOW TENSILE STRENGTH	ANY MATERIAL WHICH CAN BE DRILLED & ROLLED	PRACTICALLY UNLIMITED
NOZZLE & MANHOLE ATTACHMENT AND REINFORCEMENT		READILY ATTACHED BY WELDING	HAND FORGE WELDING TO FLUED NECKS OR SADDLES WHICH IS EXPENSIVE	DIFFICULT TO SECURE ADEQUATE LIGAMENTS BETWEEN RIVET HOLES	INVOLVES UPSETTING OR PROVISION OF EXTRA THICKNESS
UNIFORM STRENGTH ELIMINATION OF STRESS RAISERS		EASILY SECURED	EXPENSIVE WITH 100 % FORGE WELDING PAD. PADS USUALLY FUSION WELDED.	LAPS, BUTT STRAPS, RIVETS ETC. ARE STRESS RAISERS & DETRACT FROM UNIFORM STRENGTH.	SECURED AT EXTRA EXPENSE UNLESS FUSION WELDING IS USED ON ATTACHMENTS
CONCENTRICITY		SHELLS CAN BE REROLLED AFTER WELDING LONGITUDINAL SEAMS		BUTT STRAPS CAUSE OUT OF ROUND	USUALLY MACHINED
SERVICE	HIGH TEMPERATURE	PERMITS USE OF ALMOST ALL MATERIALS. WELDS HAVE GOOD CREEP STRENGTH AND CAN BE MADE WITH GOOD IMPACT RESISTANCE	LIMITED TO LOW CARBON STEEL	BUTT STRAPS & RIVET HEADS CANNOT BE SUBJECTED TO HEAT TRANSFER. DECREASE IN YIELD STR. WITH TEMPERATURE. LOOSENS RIVETS	PERMITS USE OF ALL MATERIALS
	LOW TEMPERATURE			CAULKING AND STRESS RAISERS LOWER IMPACT RESISTANCE	
	SUDDEN CHANGES IN TEMPERATURE	GIVE SATISFACTORY SERVICE		LOOSENS RIVETS, DESTROYS CAULKING. LATER VESSELS HAVE BUTT STRAPS AND RIVETS SEAL WELDED	GIVES SATISFACTORY SERVICE
	TEMP. DIFFERENTIAL				
	MAINTENANCE	MINIMUM	MINIMUM	CAULKING & SEAL WELDING REQUIRE CONSTANT MAINTENANCE	MINIMUM
	REPAIRS & CHANGES	READILY MADE	MUST BE MADE BY ARC WELDING	RIVET REPAIRS EXPENSIVE	MUST BE MADE BY ARC WELDING

FIELD CONSTRUCTION	PRACTICAL	NOT PRACTICAL	GENERALLY PRACTICAL	LIMITED TO SHOP WORK
YIELDING	SOME YIELDING POSSIBLE WITHOUT FAILURE		YIELDING CAUSES LEAKS	SOME YIELDING POSSIBLE WITHOUT FAILURE
FLEXIBILITY CLASS OF CONSTRUCTION	TYPE OF JOINT WITH OR WITHOUT STRESS RELIEVING AND RADIOGRAPHING SELECTED TO SUIT SERVICE	ONE CLASS OF CONSTRUCTION	TWO CLASSES OF CONSTRUCTION	ONE CLASS OF CONSTRUCTION
CORROSION	UNIFORM SURFACE-WELD USUALLY AS RESISTANT AS PLATE-HEAT TREATMENT FLEXIBLE	UNIFORM SURFACE	DIFFICULT TO PROVIDE CORROSION ALLOWANCE ON RIVET HEADS, CORROSION ACCELERATED AT RIVET HEADS	UNIFORM SURFACE
FATIGUE STRESS CORROSION CORROSION FATIGUE EMBRITTLEMENT	RESISTANCE IMPROVED BY STRESS RELIEVED VESSEL		STRESS RAISERS AND LACK OF STRESS RELIEF LOWER RESISTANCE	RESISTANCE IMPROVED BY STRESS RELIEVED VESSEL
INSPECTION OF SEAMS & DETECTION OF DEFECTS	NON-DESTRUCTIVE TESTS, RADIOGRAPH, MAGNETIC PARTICLE, PENETRANT OIL.	VISUAL	VISUAL	HOT WORK REVEALS DEFECTS BUT SOMETIMES COVERS THEM OVER. MACHINED SURFACE ENABLES GOOD CHECK.
HUMAN ELEMENT	AVAILABLE INSPECTION MEANS & AUTOMATIC WELDING OFFER POSSIBILITY OF MINIMIZING	SKILL OF WELDER DETERMINES QUALITY OF JOINT	MECHANICAL EQUIPMENT CAN PRODUCE UNIFORM RESULTS	IMPORTANT. HOWEVER, PLATE OR HOT WORKED MATERIAL INVOLVES SAME CONSIDERATION

Table 2—Requirements of Production Tests on Groove Welds

CODE OR REGULATIONS	A.S.M.E BOILER CODE	A.S.M.E U68 UNFIRED PRESSURE VESSEL CODE	A.P.I.-A.S.M.E. CODE	AMERICAN BUREAU OF SHIPPING	U.S. COAST GUARD	U.S. NAVY
TEST PLATE MATERIAL	SAME SPECIFICATION AS USED IN DRUM AND SAME THICKNESS AS SHELL PLATE.		SAME SPECIFICATION AND PREFERABLY SAME PLATE AS VESSEL	SAME SPECIFICATION AS USED IN DRUM AND SAME THICKNESS AS SHELL PLATE		CUT FROM SAME PLATE AS USED IN SHELL
NUMBER OF TEST PLATES REQUIRED	ONE PER DRUM BUT SEE NOTE 1	ONE PER DRUM BUT SEE NOTE 2	ONE PER EACH TYPE WELDED JOINT USED IN VESSEL BUT SEE NOTE 3	ONE PER DRUM	ONE PER DRUM BUT SEE NOTE 4	ONE PER DRUM
TRANSVERSE TENSION TEST	ONE REQUIRED	ONE REQUIRED	EITHER ONE REQUIRED OR ONE ALL WELD TENSILE TEST.	TWO REQUIRED	ONE REQUIRED	NOT REQUIRED
REQUIRED PROPERTIES	ULTIMATE TENSILE STRENGTH NOT LESS THAN MIN OF BASE PLATE		SEE NOTE 5	ULTIMATE TENSILE STRENGTH NOT LESS THAN MIN. OF BASE PLATE		
FREE FACE BEND	ONE REQUIRED	ONE REQUIRED	ONE REQUIRED	TWO REQUIRED	ONE REQUIRED	NOT REQUIRED
REQUIRED PROPERTIES	MIN OF 30% ELONGATION ACROSS WELD	MIN. OF 30% ELONGATION ACROSS WELD OR $\frac{700000}{U}+20$ WHERE U = MIN. T.S OF BASE ℄	MINIMUM OF 30% ELONGATION ACROSS WELD FOR STRESS RELIEVED WELDS MINIMUM OF 20% ELONGATION ACROSS WELD FOR UNSTRESS RELIEVED WELDS			
ALL WELD TENSILE TEST	ONE REQUIRED	ONE REQUIRED	EITHER ONE REQUIRED OR ONE TRANSVERSE TENSILE TEST	NOT REQUIRED	NOT REQUIRED	ONE REQUIRED
REQUIRED PROPERTIES	TENSILE STRENGTH NOT LESS THAN MINIMUM OF BASE PLATE					TENSILE STRENGTH NOT LESS THAN MIN. OF BASE PLATE - MIN OF 25% ELONGATION IN 2 IN.
	MIN. OF 20% ELONGATION IN 2 IN.	MIN. OF 20% ELONGATION IN 2 IN. OR $\frac{700000}{TS}+10$	MIN. OF 20% IF STRESS RELIEVED MIN. OF 15% IF NOT.			
FREE REVERSE BEND	NOT REQUIRED	NOT REQUIRED	ONE REQUIRED	NOT REQUIRED	ONE REQUIRED FOR LESS THAN 3/4" THICKNESS	NOT REQUIRED
REQUIRED PROPERTIES			SAME AS FREE FACE BEND		SAME AS FREE FACE BEND	
GUIDED BEND TEST	NOT REQUIRED	NOT REQUIRED	NOT REQUIRED	UP TO 3/4" THICKNESS TWO FACE AND ROOT BEND TESTS REQUIRED. 3/4" AND OVER FOUR SIDE BEND TESTS REQUIRED.	ONE SIDE BEND TEST REQUIRED FOR OVER 3/4" THICKNESS	TWO SIDE BEND TEST REQUIRED
REQUIRED PROPERTIES				NO DEFECT ON TENSION SURFACE OF DIMENSION GREATER THAN 1/8 IN. ANY DIRECTION IS PERMISSIBLE		
NICK BREAK TEST	NOT REQUIRED	NOT REQUIRED	ONE REQUIRED	NOT REQUIRED	NOT REQUIRED	NOT REQUIRED
REQUIRED PROPERTIES			SEE NOTE 6			
IMPACT TEST	NOT REQUIRED	TEST OF PLATE, WELD, HEAT AFFECTED ZONE AT LOWEST OPERATING TEMP. ONLY IF VESSEL MAY OPERATE BELOW 20°F.	NOT REQUIRED	NOT REQUIRED	NOT REQUIRED	NOT REQUIRED
REQUIRED PROPERTIES		MIN. OF 15 FT. LB. CHARPY				

NOTE 1 - WHEN THERE ARE SEVERAL PRESSURE PARTS BEING WELDED IN SUCCESSION ON ANY ONE ORDER, THE PLATE THICKNESSES OF WHICH FALL WITHIN A RANGE OF 1/4 INCH, WITH DIAMETERS DIFFERING NOT MORE THAN 6 INCHES, AND OF THE SAME GRADE OF MATERIAL, A TEST PLATE SHALL BE FURNISHED FOR EACH 200 LINEAR FEET, OR FRACTION THEREOF, OF THE MAIN WELDED JOINTS.

NOTE 2 - WHEN THERE ARE SEVERAL VESSELS BEING WELDED IN SUCCESSION OR AT ANY ONE TIME THE PLATE THICKNESSES OF WHICH FALL WITHIN A RANGE OF 1/4 INCH, EACH 200 FT OF LONGITUDINAL AND CIRCUMFERENTIAL SEAMS MAY BE CONSIDERED AS THE EQUIVALENT OF ONE VESSEL.

NOTE 3 - WHEN SEVERAL VESSELS OF THE SAME GRADE OF MATERIAL AND VARYING IN PLATE THICKNESSES BY NOT MORE THAN 1/4 INCH ARE TO BE MADE AT THE SAME TIME, ONE TEST PLATE FOR EACH TYPE OF WELDED JOINT SHALL BE ACCEPTED FOR THE AMOUNT OF COMPLETED SEAMS AS LISTED BELOW:

FOR PLATE OVER 1 1/4 IN IN THICKNESS — 100 LINEAR FEET
FOR PLATE 1/2 TO 1 1/4 IN IN THICKNESS — 200 LINEAR FEET
FOR PLATE UNDER 1/2 IN IN THICKNESS — 300 LINEAR FEET

NOTE 4 - WHEN SEVERAL VESSELS FABRICATED OF CARBON STEEL PLATE ARE BEING WELDED IN SUCCESSION OR AT ANY ONE TIME THE PLATE THICKNESSES OF WHICH FALL WITHIN A RANGE OF 1/4 IN., EACH 50 LINEAR FEET OF LONGITUDINAL AND CIRCUMFERENTIAL JOINTS MAY BE CONSIDERED THE EQUIVALENT OF ONE VESSEL.

NOTE 5 - EACH REDUCED-SECTION TENSION-TEST SPECIMEN SHALL HAVE AN ULTIMATE TENSILE STRENGTH COMPUTED FROM THE AREA OF THE BASE-METAL SECTION THAT IS NOT LESS THAN THE MINIMUM OF THE SPECIFIED TENSILE RANGE OF THE PLATE MULTIPLIED BY 1.3 TIMES THE FINAL JOINT EFFICIENCY, EXCEPT THAT IN NO CASE NEED IT BE HIGHER THAN THE MINIMUM SPECIFIED TENSILE STRENGTH OF THE PLATE.

NOTE 6 - THE FRACTURE OF THE WELD SHALL SHOW COMPLETE PENETRATION THROUGHOUT THE ENTIRE THICKNESS OF THE WELD, ABSENCE OF OXIDE OR SLAG INCLUSIONS, AND A DEGREE OF POROSITY NOT TO EXCEED SIX GAS POCKETS PER SQUARE INCH OF THE TOTAL AREA OF THE WELD SURFACE EXPOSED IN THE FRACTURE, THE MAXIMUM DIMENSION OF ANY SUCH POCKET NOT TO BE IN EXCESS OF 1/16 IN.

Table 3—Comparison of Requirements of ASME Boiler Code and API-ASME Code (1947 Rev.)

CODE	API-ASME CODE FOR UNFIRED PRESSURE VESSELS FOR PETROLEUM LIQUIDS AND GASES				ASME CODE FOR UNFIRED PRESSURE VESSELS					ASME POWER BOILER CODE
NOMINAL FACTOR OF SAFETY	4				4		5			5(2)
CLASS OF CONSTRUCTION AND TYPE OF JOINT	SINGLE FULL-FILLET LAP FOR ATTACHING HEADS CONVEX TO PRESSURE ONLY	FOR GIRTH JOINT ONLY: DOUBLE FULL FILLET LAP OR SINGLE FULL FILLET LAP WITH PLUG WELDS	SINGLE WELDED BUTT WITHOUT BACKING STRIP	DOUBLE WELDED BUTT OR SINGLE WELDED BUTT WITH BACKING STRIP	U-201 DOUBLE WELDED BUTT OR EQUIVALENT SINGLE WELDED BUTT	U-200 DOUBLE WELDED BUTT OR EQUIVALENT SINGLE WELDED BUTT	U-70 SINGLE WELDED BUTT TO 1/4" DOUBLE WELDED LAP TO 3/8" DOUBLE WELDED BUT TO 5/8"	U-69 DOUBLE WELDED BUTT OR EQUIVALENT SINGLE WELDED BUTT	U-68 DOUBLE WELDED BUTT OR EQUIVALENT SINGLE WELDED BUTT	DOUBLE WELDED BUTT OR EQUIVALENT SINGLE WELDED BUTT
RADIOGRAPHING REQUIRED	REQUIRED FOR ASTM A-212 AND A-225 FOR CERTAIN THICKNESSES AND PLATE QUALITY; OTHERWISE OPTIONAL				SPOT RADIOGRAPH OR SECTIONING	YES	NO	NO	YES	YES
STRESS RELIEVING REQUIRED	SEE NOTE (4)				SEE NOTE (4)	YES	NO	SEE NOTE (4)	YES	YES
JOINT EFFICIENCY %	(3) SR 58 SR 55	(3) SR 69 SR 65	(3) SR 74 SR 70	(3) XR-SR 95 XR 90 SR 85 NSR 80	80	95(1)	VALUE OF SE DEPENDS ON TYPE WELD & THICKNESS	80	90 95(1)	90 95(1)
DESIGN FORMULAS — SERVICE	PETROLEUM AND AUXILIARY VESSELS				NOT FOR LETHAL GAS OR LIQUID	NONE	NOT FOR LETHAL GAS OR LIQUID	NOT FOR LETHAL GAS OR LIQUID	NONE	STEAM GENERATION
MIN. PRESS. AND SIZE	(P-15) (D-4) > 60 (P-15) (V-1.5) > 22.5				P > 15 D > 6					—
MAX. PRESSURE PSI	NONE				600	3000	200	600	3000	NONE
MAX. OR MIN. TEMPERATURE	1000° F. MAX. (CARBON AND CARBON MOLY STEEL) NO PROVISIONS BELOW MINUS 20° F.				TEMP FOR WHICH ALLOWABLE STRESS IS GIVEN IMPACT TESTS REQUIRED BELOW MINUS 20° F.		250° F.	TEMPERATURE FOR WHICH ALLOWABLE STRESS IS GIVEN		
MAXIMUM THICKNESS	5/8 IN.	5/8 IN.	5/8 IN.	SINGLE WELDED LIMITED TO 1 1/4"	1 1/2 IN.	NONE	5/8 IN.	1 1/2 IN.	NONE	NONE
SHELL THICKNESS	$t = \frac{PD}{2SE-P} + C$ FOR $t > 0.1D$ USE LAMÉ FORMULA				$t = \frac{PD}{2SE-1.2P} + C$ FOR $t > 0.25D$ USE LAMÉ FORMULA					$t = \frac{PD}{2SE-1.2P} + C$
HEMISPHER. HEADS	$t = \frac{PD(MEAN)}{4SE} + C$				$t = \frac{PD}{4SE} + C$ FOR t UP TO $0.1D$					
ELLIPSOIDAL HEADS	$t = \frac{PD(MEAN)V}{2SE} + C$ V=1 FOR RATIO 2:1				$t = \frac{PD}{2SE-1.2P} + C$ FOR 2:1 AXIS RATIO					
DISHED HEADS	$t = W\frac{PR}{2SE} + C$ W VARIES FROM 1 TO 1.76 WITH $\frac{\text{KNUCKLE RAD}}{\text{CROWN RAD.}}$				$t = \frac{5PR}{6SE} + C$ R = CROWN RADIUS					

DESIGN FORMULAS	CONICAL HEADS	$t = \frac{PD(MEAN)}{2SE\ COS\ \alpha} + C$ α 1/2 APEX ANGLE	$t = \frac{PD}{2\ COS\ \alpha\ (SE-0.6P)} + C$ CORNER RADIUS REQUIRED IF α EXCEEDS 30°				—
	FLAT HEADS	$t = D\sqrt{\frac{C \times P}{S}}$ WHERE "C" IS A CONSTANT WHICH VARIES WITH THE TYPE OF ATTACHMENT :- ALL CODES HAVE SAME FACTORS.					
	BOLTED FLANGES (NON ASA)	SPECIAL RULES MANDATORY EXCEPT FOR GASKET FACTORS					
UNREINFORCED SHELL OPENINGS MAX. SIZE		2 IN	DEPENDS ON RATIO OF SHELL THICKNESS REQUIRED TO THICKNESS AVAILABLE & ON PRODUCT OF VESSEL DIA. X THICKNESS — MAX. = 8 IN.				
REINFORCED SHELL OPENINGS AREA TO BE REPLACED		DIAMETER OF CORRODED OPENING X REQUIRED THICKNESS, WITH E = 1	DIAMETER OF CORRODED OPENING LESS 2 IN. X REQUIRED THICKNESS, WITH E = .90.				
ATTACHMENT WELDS		SHEAR FACTOR VARIES WITH DIRECTION OF LOADING	SHEAR FACTOR = .8				
HYDROSTATIC TEST PRESSURE PSI		1 1/2 X ALLOWABLE WORKING PRESSURE (BASED ON UNCORRODED TEST CONDITION)	2 X ALLOWABLE WORKING PRESSURE STAMPED ON VESSEL (CORRECTED FOR TEMPERATURE)				1.5 OR 2X ALL. W. P. DEPENDING ON BOILER TYPE & DESIGN STRESS
HAMMER TEST		REQUIRED IF HYD TESTED & NOT RADIOGRAPHED AND STRESS RELIEVED	REQUIRED	NOT REQUIRED	REQUIRED	NOT REQUIRED	NOT REQUIRED
PNEUMATIC TEST PRESSURE PSI		1.1 X ALLOWABLE WORKING PRESSURE	1 1/4 X ALLOWABLE WORKING PRESSURE				

NOTES -

(1) WELD REINFORCEMENT MUST BE REMOVED SUBSTANTIALLY FLUSH WITH SURFACE OF PLATE (MANDATORY FOR U-200 VESSELS AND FOR 95% EFF. VESSELS)

(2) FOR $t > 1/2$ IN "S" MAY BE INCREASED 25% PROVIDED AN ADDITIVE THICKNESS OF 0.1 IN. IS INCLUDED IN THE THICKNESS AND CERTAIN RESTRICTIONS ARE COMPLIED WITH. SAFETY FACTOR MAY THUS APPROACH 4 FOR HEAVY THICKNESSES.

(3) X R DENOTES RADIOGRAPHING PERFORMED. S R DENOTES STRESS RELIEVING PERFORMED N S R DENOTES NO STRESS RELIEVING PERFORMED. EFFICIENCIES SHOWN ARE FOR FIREBOX QUALITY PLATE. EFFICIENCIES ARE LOWER FOR FLANGE OR STRUCTURAL QUALITY PLATE.

(4) STRESS RELIEVING IS REQUIRED IF THE THICKNESS AT MAIN SEAMS EXCEEDS 1 1/4 IN. OR WHERE IT EXCEEDS 0.58 IN. BUT IS LESS THAN (D + 50) 1/120. IT IS ALSO REQUIRED FOR CERTAIN HIGH TENSILE AND ALLOY STEELS IN ALL OR LESSER THICKNESSES.

SYMBOLS NOT EXPLAINED IN TABLE :-

P = PRESSURE, PSI

D = DIAMETER, IN. (INSIDE UNLESS NOTED)

R = RADIUS, IN.

V = VOLUME, CU. FT.

S = ALLOWABLE STRESS (PSI) GIVEN IN APPLICABLE CODE FOR CLASS OF CONSTRUCTION AND PART INVOLVED.

E = JOINT EFFICIENCY, (DECIMAL)

C = CORROSION ALLOWANCE, IN.

t = THICKNESS, IN.

has not been adopted, but the change is being carefully investigated and considered; several large welded locomotive boilers have been in operation since early 1946 and many more either have had lesser service or are under construction.

GOVERNING CODES AND REGULATIONS

In view of the pressures and temperatures under which industrial vessels may operate and the nature of their contents, it is apparent that substantial hazard is involved in failure. Accordingly, safety codes have been prepared to cover the construction of steam-generating equipment and pressure vessels.

At present the construction of welded boilers and pressure vessels is regulated by the codes and specifications which, with their sponsors, are listed below:

1. ASME Boiler Construction Code; American Society of Mechanical Engineers:
   Section I—Power Boilers
   Section II—Materials
   Section III—Boilers of Locomotives
   Section IV—Low-Pressure and Heating Boilers
   Section V—Miniature Boilers
   Section VI—Rules for Inspection
   Section VII—Suggested Rules for Care of Power Boilers
   Section VIII—Unfired Pressure Vessels
   Section IX—Welding Qualifications
2. API-ASME Code—Unfired Pressure Vessels for Petroleum Liquids and Gases; American Petroleum Institute and American Society of Mechanical Engineers.
3. General Specifications for Building Naval Vessels; United States Navy Department, Bureau of Ships.
4. Marine Engineering Regulations and Material Specifications; United States Coast Guard.
5. ABS Rules for Building and Classing Steel Vessels; American Bureau of Shipping.
6. Standards; Tubular Exchanger Manufacturers' Association, Inc.
7. Lloyd's Rules and Regulations; Lloyd's Register of Shipping.
8. Various State and City Codes or Regulations.
9. Various Foreign Codes or Regulations.

The above codes cover permissible materials, size, shape, design, service limitations, fabrication, heat treatment, inspection and testing requirements, and, in addition, contain requirements for the qualification of welding procedures and operators. A comparison of requirements for vessel test plates in different codes is given in Table 2, and a comparative tabulation of other requirements of the more generally used ASME and API-ASME Codes for various classes of construction is shown in Table 3.

The existence of several codes is a source of confusion and annoyance to manufacturers and users. The API-ASME Code enjoys wide acceptance in the petroleum industry and the ASME Boiler Code in other fields except for applications subject to federal control. Those States and municipalities having regulations for the most part have adopted the ASME Boiler Code in its entirety, in part or with certain exceptions. Where in doubt it is desirable to ascertain the requirements from local authorities. The ASME Power Boiler Code is mandatory in more than half of the States, the District of Columbia, Hawaii and the Canal Zone, the Provinces of Canada, with the rules for other types of boilers either mandatory or acceptable. The ASME Unfired Pressure Vessel Code is mandatory in nine states, the District of Columbia and Hawaii, the Provinces of Canada, and is required for air tanks in two states.

The ASME Boiler Code, however, is constantly undergoing revision to keep pace with improvements and to correct weaknesses in existing rules. Since many local regulations are statutory, changes can be accomplished only yearly, resulting in temporary difficulties.

There is now under consideration a proposed complete revision of Section VIII ASME *Unfired Pressure Vessel Code* which has been drafted to consolidate the best features of the present Code and those of the API-ASME Code into one set of rules. If acceptable to the ASME and API, the API-ASME Code will no longer be necessary. Similarly, the Coast Guard is revising its rules in an attempt to bring them into closer agreement with the ASME Boiler Code Rules.

MATERIALS

General

Fortunately for the early advocates of

welding, boiler drums and pressure vessels were then operated under such conditions that satisfactory and economical construction was obtained with plain carbon steels of moderate tensile strength. For example, drum plate material was confined to conventional flange and firebox grades of 55,000 or 60,000 psi. minimum tensile strength. This type of steel, for many years the outstanding material for riveted construction, was suitable for arc and gas welding. This same general class of material was used for other component parts of pressure vessels and auxiliary equipment such as headers, piping, boiler tubes and superheater and economizer tubular elements. With the application of increasingly higher operating pressures and temperatures in power plant and industrial process equipment, the situation has appreciably changed not only by the introduction of alloy steels having special properties but by the development of new methods of fabrication.

Extreme conditions of present-day operation include: boiler pressures up to 2600 psi.; superheated steam temperatures up to 1400°F.; process vessel service up to 1200°F. and as low as minus 350°F. Each set of operating conditions emphasizes specific requirements which must be considered in the selection of suitable material. Higher operating pressures for a vessel of given diameter involve either an increase in wall thickness or the use of higher strength material. At temperatures in excess of approximately 650°F., low-carbon steels suffer a loss in tensile properties and undergo plastic flow or creep, while steels having suitable alloying elements possess greater strength and creep resistance, thus permitting the use of higher working stresses. In the low temperature range of operation, i.e., at temperatures lower than 0°F., material should be examined with particular reference to notch toughness and resistance to brittle fracture.

When steel is subjected to stress at elevated temperature for extended periods of time, slow plastic deformation or creep occurs. By creep strength is usually meant the stress at any given temperature which will produce a specified low deformation rate such as 1% in 10,000 hr. or 1% in 100,000 hr. When such tests are run sufficiently long, rupture occurs providing *stress-rupture* data, the rupture strength being the stress which will produce rupture in the specified interval of time. Elongation at failure is also recorded in rupture tests. Creep and rupture tests are rarely run for sufficiently long periods to simulate service requirements. Instead, estimated values are derived from tests of shorter duration, about 1000 hr. being considered necessary for reasonably dependable extrapolation. Figure 1 shows the comparative creep strengths of some of the most commonly used steels.

The following properties of material are important in connection with the choice of the most suitable and economical material for a particular application:

1. Short time tensile strength at room and at maximum operating temperature.
2. Short time ductility at room and at maximum operating temperature.
3. Short time yield strength at room and at maximum operating temperature.
4. Resistance to deterioration by corrosion, corrosion fatigue, stress corrosion, etc.
5. Notch sensitivity and impact resistance (particularly for subnormal temperatures).
6. Creep strength (for service temperatures in plastic flow range).
7. Rupture strength and ductility (for service temperatures in plastic flow range).
8. Physical structure stability under intended service conditions.
9. Age hardening and embrittlement under intended service conditions.
10. Weldability and need for special preheat and postheat treatments.
11. Work hardening characteristics.
12. Thermal conductivity and thermal shock resistance.
13. Resistance to repeated applications of load (fatigue)

The materials generally employed in boilers and pressure vessels may be grouped as follows:

Plain carbon steels—rimmed, semi-killed and killed
Low-alloy steels
Straight chromium steels
Austenitic steels
Integral clad steels
Nonferrous materials

Table 4 lists the plate materials most commonly used in pressure vessel construction with a summary of tensile and chemical requirements. In most cases,

parallel specifications are available for forgings, pipe and castings.

Plain Carbon Steels

Specifications for rimmed or semi-killed carbon steel plate were inherited from riveted and forge-welded construction. These steels contain an average of approximately 0.20 to 0.30% carbon and, although the welding quality of these steels has been improved, the specifications themselves are very little different from what they were twenty years ago. Almost all of the plate used in pressure vessels up to $1^1/_2$ in. thick for ordinary service is of this type. The firebox grade is preferred for premium construction because of the usually greater uniformity in chemistry and cleanliness. The API-ASME Pressure Vessel Code assigns a quality factor of 1.00 for welds in firebox steel and 0.97 in flange quality steel. This code also permits the use of structural quality plate conforming to ASTM Specifications A-7 and A-283 for service up to 750°F. and $^3/_4$ in. thickness with a quality factor of 0.92.

All carbon steel plates more than 2-in. thick and the higher strength 65,000 and 70,000 psi. tensile strength grades are

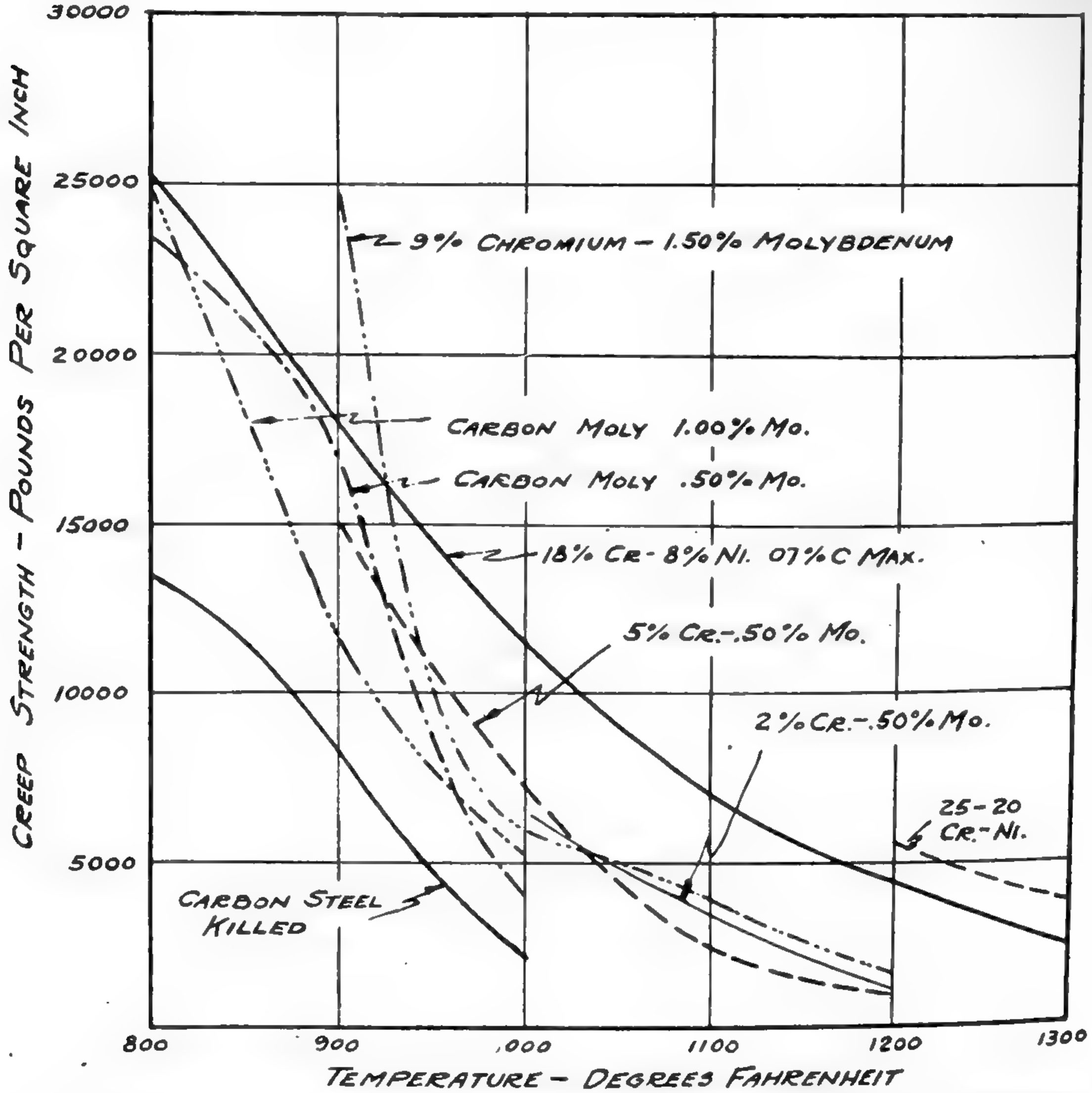


Fig. 1.—Curves Showing Comparative Creep Strengths of Various Steels. Rate, 1% in 100,000 Hr.

silicon killed in all thicknesses. Some specifications for carbon steel pipe permit the use of rimmed steel, although most seamless piping is made of killed steel. The ASME Boiler Code recognizes two grades of killed-steel pipe, one in which the silicon content is less than 0.10% and the other in which it is 0.10% minimum and has established allowable working stresses at elevated temperatures for each.

Low-Alloy Steels

There are a number of low-alloy steels which possess one or more of the following properties as compared with plain carbon steels:

Improved room temperature strength.
Improved high temperature strength.
Greater resistance to impact at low temperatures.
Improved corrosion resistance.
Improved oxidation resistance and stability at high temperatures.

Chromium-manganese-silicon steel possesses the first of these characteristics and also resistance to atmospheric corrosion; nickel steel possesses the first and third; carbon-molybdenum steel possesses the second; 2% chromium–$^1/_2$% molybdenum, $2^1/_4$% chromium–1% molybdenum, 5% chromium–$^1/_2$% molybdenum steels and steels of similar analyses possess the second, fourth and fifth of these characteristics. Standard plate specifications for the chromium-molybdenum steels, last mentioned above, are still not available. Five percent chromium–$^1/_2$% molybdenum steel is used mainly in the oil-refinery industry due to its high strength at elevated temperatures and its resistance to sulfur corrosion.

Steels in this group require greater care in welding than plain carbon steels and should usually be thermally stress relieved.

Straight Chromium Steels

The straight chromium steels are relatively little used for pressure parts, except for handling nitric acid. They are used extensively as corrosion protective linings in the oil and chemical fields. AISI types 410 and 430 modified are permissible for ASME Code U-68 vessels under the provisions of ASME Boiler Code Case No. 989. These steels, in general, show greater notch sensitivity than plain carbon steels, this effect increasing with increased chromium content particularly in the range above 15% chromium. Steels with a chromium content above 13% are also subject to the possibility of temper embrittlement following service at temperature in the 700 to 1000°F. range. (See Chapter 30.)

Austenitic Steels

The most common of the austenitic chromium-nickel stainless steels are AISI Types 304, 316 and 347, which find considerable use in the chemical and petroleum field. They are used both for pressure parts and internal linings. They are suitable for very low-temperature service, maintaining good impact resistance at minus 300°F., corrosion resistance, and possess substantial high temperature creep and rupture strength. In this group, the ASME Code contains material specifications for chromium-nickel steels, which are modifications of AISI Types No. 304, 316, 321 and 347 and rules for their use in Case No. 897 Other analyses in this group which find occasional use in pressure vessel construction but which are not as yet included in codes are 25–12 and 25–20 chromium-nickel steels. They have superior strength to 18% chromium, 8% nickel steel in the extremely high temperature range. The austenitic steels are nonmagnetic and non-air-hardening but work-harden readily. Their low thermal conductivity and consequent lower resistance to thermal shock is a factor to be considered for severe service. (See Chapter 31.)

Integral Clad Steels

Carbon or low-alloy steel plates with an integral cladding of alloy steel (304, 347, 316 and 405, 410 and 430), nickel, Monel or Inconel find considerable application in pressure vessel construction because of the corrosion protection afforded at lower cost than for solid corrosion-resisting materials. Such materials conforming to ASTM Specifications A263, A264 and A265 are permissible for Code construction. Silver- and copper-clad steels are also available. Clad steel construction is discussed more fully in Chapter 37A.

Nonferrous Materials

The ASME code covers certain non-

TABLE 4—Principal Materials Used in Pressure Vessel Construction, (Standard Specifications with Summary of Tensile and Chemical Requirements)
ASTM-ASME Specifications Only

Plate Specifications	Tensile Range, Psi.	Chemical Composition, % C	Mn	S[a]	P[a]	Si	Other Elements
1. ASTM A-285-47, ASME SA-285. Carbon steel plates, low and intermediate tensile strength, of flange and firebox qualities (plates 2 in. and under in thickness)	Grade A, 45-55,000	0.15[b] / 0.17[c]	0.80 max.	0.04 max.	0.035 max.	...	...
	Grade B, 50-60,000	0.20[b] / 0.22[c]	0.80 max.	0.04 max.	0.035 max.	...	...
	Grade C, 55-65,000	0.25[b] / 0.30[c]	0.80 max.	0.04 max.	0.035 max.	...	...
2. ASTM A-201-47, ASME SA-201. Carbon silicon steel plates of ordinary tensile ranges for fusion welded boilers and other pressure vessels	Grade A, 55-65,000	0.20 / 0.24 / 0.27 / 0.31 / 0.35 [d]	0.80 max.	0.04 max.	0.035 max.	0.15-0.30	...
	Grade B, 60-70,000	0.24 / 0.27 / 0.30 / 0.35 [d]	0.80 max.	0.04 max.	0.035 max.	0.15 0.30	...
3. ASTM A-212-47, ASME SA-212. Carbon silicon steel plates, high tensile strength, for boilers and other pressure vessels (plates 6 in. and under in thickness)	Grade A, 65-77,000	0.28 / 0.31 / 0.33 [e]	0.90 max.	0.04 max.	0.035 max.	0.15-0.30	...
	Grade B, 70-82,000	0.31 / 0.33 / 0.35 [e]	0.90 max.	0.04 max.	0.035 max.	0.15-0.30	...
4. ASTM A-204-47, ASME SA-204. Molybdenum steel plates for boilers and other pressure vessels	Grade A, 65-77,000	0.18 / 0.21 / 0.23 / 0.25 [f]	0.90 max.	0.04 max.	0.035 max.	0.15-0.30	0.40-0.60 Mo
	Grade B, 70-82,000	0.20 / 0.23 / 0.25 / 0.27 [f]	0.90 max.	0.04 max.	0.035 max.	0.15-0.30	0.40-0.60 Mo
	Grade C, 75-87,000	0.23 / 0.26 / 0.28 [f]	0.90 max.	0.04 max.	0.035 max.	0.15-0.30	0.40-0.60 Mo
5. ASTM A-202-47, ASME SA-202. Chromium, manganese, silicon (CMS) alloy steel plates for boilers and other pressure vessels	Grade A, 75-90,000	0.17 max.	1.05-1.40	0.04 max.	0.035 max.	0.60-0.90	0.30-0.60 Cr
	Grade B, 85-100,000	0.25 max.	1.05-1.40	0.04 max.	0.035 max.	0.60-0.90	0.30-0.60 Cr

6. ASTM A-203-47T, ASME SA-203. Nickel steel plates for boilers and other pressure vessels	Grade A or D, 65-77,000	0.17 / 0.20 / 0.23 [g]	0.80 / 0.90 / 0.90 [g]	0.04 max.	0.035 max.	0.15–0.30	
	Grade B or E, 70-82,000	0.20 / 0.23 / 0.25 [g]	0.80 / 0.90 / 0.90 [g]	0.04 max.	0.035 max.	0.15–0.30	Grades A, B, C 2.00–2.75 Ni
	Grade C, 75-87,000	0.25 / 0.27 [g]	0.80 / 0.90 [g]	0.04 max.	0.035 max.	0.15–0.30	Grades D, E 3.00–3.75 Ni
7. ASTM A-225-47, ASME SA-225. Manganese vanadium steel plates for boilers and other pressure vessels	Grade A, 70-82,000	0.18 max.	1.45 max.	0.04 max.	0.035 max.	0.15–0.30	0.08–0.14 V
	Grade B, 75-87,000	0.20 max.	1.45 max.	0.04 max.	0.035 max.	0.15–0.30	0.08–0.14 V
8. ASTM A266-44T, ASME SA-266. Carbon steel seamless drum forgings	Grade I, 60,000 min.	0.35 max.	0.40–0.90	0.04 max.	0.04 max.	0.15–0.30	...
	Grade II, 70,000 min.	0.35 max.	0.40–0.90	0.04 max.	0.04 max.	0.15–0.30	...
	Grade III 75,000 min.	0.50 max.	0.50–0.90	0.04	0.04	0.30 max.	...
9. ASTM A-240-44, ASME SA-240. Corrosion resisting chromium and chromium-nickel steel plate, sheet and strip for fusion welded unfired pressure vessels	Grade S, 75,000 min.	0.08 max.	2.5 max.	0.03 max.	0.035 max.	0.85 max.	18 min. Cr, 8 min. Ni
	Grade M, 75,000 min.	0.08 max.	2.5 max.	0.03 max.	0.035 max.	0.85 max.	17 min. Cr, 10 min. Ni, 2.00 min. Mn
	Grade C, 75,000 min.	0.08 max.	2.5 max.	0.03 max.	0.035 max.	0.85 max.	17 min. Cr, 9.5 min. Ni, 10×C, min. Cb, 1.00 max. Cb
	Grade T, 75,000 min.	0.08 max.	2.5 max.	0.03 max.	0.035 max.	0.85 max	17 min. Cr, 9.0 min. Ni, 5×C, min. Ti, 0.60 max. Ti

[a] For firebox quality steel, made by basic open-hearth process.
[b] For plates 3/4 in. and under in thickness, firebox quality only.
[c] For plates over 3/4 in. to 2 in., inclusive, in thickness, firebox quality only.
[d] Carbon content progressively higher for plates 1 in. and under, over 1 in. to 2 in., over 2 in. to 4 in., over 4 in. to 8 in., over 8 in. to 12 in. (Grade A only) in thickness. Flange quality is limited to 2 in. thickness maximum.
[e] Carbon content progressively higher for plates 1 in. and under, over 1 in. to 2 in., over 2 in. to 6 in., in thickness.
[f] Carbon content progressively higher for plates 1 in. and under, over 1 in. to 2 in., over 2 in. to 4 in., over 4 in. to 6 in., in thickness.
[g] Carbon and manganese content progressively higher for plates up to 2 in., inclusive, over 2 in. to 4 in., over 4 in. to 6 in., in thickness; no C, D and E Grades above 4 inches.

ferrous materials which are applicable to arc-welded pressure vessels as follows:

Aluminum-Manganese	(ASTM B196)
Nickel-Copper Alloy	(ASTM B127)
Copper-Silicon	(ASTM B96)
Deoxidized Copper	(ASTM B11, 12, 13, 42)

It is expected that the Code will shortly extend the scope of its rules considerably to cover other nonferrous materials.

Allowable Stresses and Joint Efficiencies

Material properties which influence load-carrying ability and general suitability for a particular service have been listed at the beginning of this section. These properties are significant only in proportion to the adequacy of the test procedure from which they are determined, and since in most cases small specimens with elementary types of loading are used, the test results are of qualitative rather than quantitative significance. Physical metallurgy has not yet provided a suitable understanding of modes of failure and its association with stiffness, ductility, resistance to shock and fatigue and other material properties. For the present, allowable stresses are necessarily selected for commonly used materials by giving primary weight to established safe usage, and permitting comparable service on other materials in proportion to their properties as determined by conventional tests. Actually tensile strength, yield point, creep strength or long-time rupture strength, determine present-day allowable stresses, ductility and shock and fatigue resistance being taken care of in some degree by material specifications and other test requirements. With further progress, creep and rupture tests will possibly contribute more than comparative evaluation and the selection of allowable stresses may reflect better evaluation of the flow characteristics, rupture patterns and ductility as determined by these tests. Proper selection of working stresses also involves design and service considerations, which will be considered more broadly under Design.

These material properties and, in addition, the influence of abrupt structural discontinuity (plate—heat affected zone—weld) and the unworked deposited metal attendant to welding must be considered in establishing joint efficiencies. There is a tendency to overvalue the greater tensile strength of many welds with perhaps too little attention to lower ductility in the heat-affected zone, which is the critical area for failure under sudden or repeated loading. On materials which undergo transformation, full heat treatment is beneficial in minimizing this weld edge discontinuity, subcritical stress relief being of only nominal benefit. Joint efficiencies also depend on design and inspection requirements and are discussed further under Design.

Selection of Material

Table 5 contains a brief and partial summary which will give some idea of the present practice in selecting steels for various services. Selection in any individual case will be influenced by economics, corrosion resistance, desired quality, ease of making field changes, etc. The temperature range shown is intended to indicate the range of general usage and does not indicate the limits to which the steel can be used.

DESIGN

General

The application of modern welding to pressure vessels and boilers has made possible improved design approaching uniform strength throughout each vessel which together with advances in mechanics and metallurgy has pointed the way to more economical use of materials. However, as a pressure membrane or uninterrupted stressed-skin structure (without butt straps, lap joints, etc.) is approached, the hazard of propagating minor flaws is increased. Also, overall economic considerations dictate design for complete rather than average safety, since damages incident to a small fraction of 1% failures would normally completely offset material and fabrication savings on the entire production. Accordingly, safety codes and designers must proceed cautiously with reduction in safety factors, considering all contributing factors (service, materials, fabrication, inspection and design) and await each advance to be adequately proved by service experience before sanctioning the next step.

The safety codes which are referred to throughout this chapter are written for the mutual benefit of manufacturer, de-

signer, user, inspector and enforcement agency. To be effective they must contain design and service requirements which are the minimum required for safety, be limited in complexity and be consistently interpreted. The designer, enforcement agency and user must evaluate special designs, unusual service requirements and other factors which either are not covered by specific rules or introduce hazards for which lower allowable stresses, better quality fabrication or special materials are required. Corrosion and other deteriorating influences vary widely with minor changes in materials or vessel contents, so that code rules necessarily apply to new construction; provisions against deterioration and for frequency of service inspection are matters of user and enforcement agency experience. Unfortunately, some forms of deterioration such as intergranular corrosion, stress corrosion and corrosion fatigue do not involve discernible loss of weight or pitting and, where suspected, visual inspection should be supplemented by all means available for the detection of fine cracks.

Pressure vessel shapes cover the entire gamut of surfaces of revolution such as cylinders, spheres, ellipsoids, torii and cones in many combinations. In addition to axially symmetrical vessels, occasional use is made of flat sides or elliptical or obround shells, with or without stiffeners or staybolts. Many considerations affect shape selection including economics (material and fabrication), space limitations and service requirements. Conventional construction employs cylindrical shell courses with either ellipsoidal or two radii torispherical heads, commonly called dished or basket heads.

Design Loading Criteria

Pressure vessels are used to contain liquids, vapors or finely-divided solid materials, singly or in combination, under pressure and temperature. Protection against excessive pressure may be obtained by designing for the maximum pressure which can be generated in the system, or more commonly, by pressure relief equipment, in which case a margin between operating and design pressure is necessary to avoid leakage at the relief mechanism. Operating pressures are left to the discretion of the designer, and are usually 5 to 25% below the maximum pressure permitted, this margin depending on degree of regulation, type of relief valves, hazards attendant to vapor discharge, etc. In code terminology the design pressure is the *maximum allowable*

Table 5—Some Applications of Materials in Pressure Vessels

Item	Service Temp., °F.	Max. Specification or Code Thickness, In.	ASTM Specification	Remarks
Boiler drums	750	12	A285 Gr. C	
Boiler drums	750	8	A201 Gr. A, Gr. B	.....
Boiler drums	750	6	A212 Gr. B, FBQ	.....
Boiler drums	750–850	6	A204, Gr. A[a] or B[a]	.....
Boiler drums	Over 850	6	1/2% Cr–1/2% Mo	.....
Pressure vessels	—20 to 750	3/4	A283, A7	For mild or relatively low hazard services[b]
Pressure vessels	—20 to 850	2	A285 Gr. C	Firebox quality used over 850°F. and generally for lower temps. also
Pressure vessels	—50 to 750	6	A212 Gr. B[a]	.....
Pressure vessels	750 to 1000	6	A204 Gr. A[a] or B[a]	Over 850°F., precautions against graphitization advisable
Pressure vessels	50 to 1000	12 8	A201 Gr. A[a], Gr. B[a]	.....
Pressure vessels	—75 to —40	6	A203 Gr. A[a] or B[a]	.....
Pressure vessels	—150 to —75	4	A203 Gr. D[a] or E[a]	.....
Pressure vessels	—300 to 1200	None	A240 Gr. S, T, C or M	Very low temp. Very high temp. Corrosion, contamination

[a] Firebox quality is customarily used by many manufacturers because of its greater dependability, although not required by codes for use below 850°F.
[b] Permitted by ASME Code for U-70 vessels not over 1/4 in. thick.

working pressure, and relief devices must reach full rated discharge capacity at 10% over this pressure (6% over in the case of boilers). The maximum temperature which the pressure shell will attain is designated the *maximum working temperature,* and may be ascertained or controlled by means of thermocouples. The maximum working pressure and temperature governing the design are required to be stamped on the vessel.

Pressure and temperature, while principal factors, are not the only design criteria. Other loadings must be considered even though the codes contain no specific rules for handling them. Such loadings include the following:

Dynamic shock; fluctuating and repeated pressure loading.

Thermal stresses; heat transfer; differential expansion; fluctuating and repeated temperature; thermal shock; start-up and shutdown effects.

Superimposed loadings; piping reactions; reactions of platforms and attached equipment.

Gradients such as varying load of contents with depth, or varying temperature in a fractionating tower.

Wind and earthquake loading.

Dead loads such as weight of vessel and contents.

Effects of supports such as lugs, saddles and skirts.

All loading does not occur simultaneously, so that parallel design conditions must sometimes be considered, such as for erection, start-up, operation, shutdown, emergency or with relief valves blowing. For example, loading under erection is usually taken at stripped weight (without insulation, piping, equipment, etc.) with full effects of wind and earthquake; loading under start-up usually assumes vessel is cold but under pressure, pipe connecting lines are hot, together with full effects of wind and earthquake.

Safe Limits for Loading

The safety of pressure equipment involves evaluation of service, materials, design, fabrication and inspection simultaneously. Since, as already pointed out, these factors individually are not susceptible to complete quantitative assessment, the only presently reliable measure of safety is reasonably extensive experience. This situation will be improved only when mechanics and metallurgy provide a sufficient understanding of the relation between stiffness, ductility, shock and fatigue.

So-called factors of safety derive quantitative significance only in relation to simplified tensile tests and do not extend in meaning beyond single applications of load; at elevated temperature they are meaningless. The original ASME Code safety factor of 5 (based on tensile strength) has been reduced to 4 in the API-ASME rules, and in the Alternate Rules of the ASME Unfired Pressure Vessel Code, with added design and fabrication restrictions. Increased stresses are also permissible on boiler drums under certain restrictions. With the variety of design and fabrication details permitted, the true safety factor is dependent on the magnitude of localized stress which exists (around openings, intersections, undercuts or at defects in welds, etc.), in combination with the resistance of the material to maintained, sudden or repeated loading.

The present basis of the ASME Boiler Construction Code allowable stress Tables P-7 and U-2 from which Table 6 herein has been prepared is covered by the following statement prepared by the ASME Subgroup on Stress Allowances for Ferrous Materials. The Alternate Rules permit stresses up to 125% of the stresses in these tables.

"The tables of allowable stresses are grouped according to temperature and in every case the temperature is understood to be the actual metal temperature.

"The stresses given in P-7 and U-2 (see Table 6) are based on 20% of the minimum tensile strength according to specifications except for bolting materials. For bolting materials the design stress is based on 16% of the minimum tensile or 20% of the yield strength for 0.2% offset, whichever is lower. (It is recognized that bolts as distinguished from other parts, are always expected to work at stresses above the design value.)

"The allowable stresses are based on 80% of the stress required to produce a creep rate of 0.01% per 1000 hours. Since 1944, stress-rupture data when available have been given consideration on the basis that the allowable stress should not exceed 50% of the stress to produce rupture at the end of 100,000 hours. However during the interval the creep data have been the limiting consideration. It should be noted that stresses set prior to

Table 6—Maximum Allowable Working Stresses for Ferrous Plate Materials (Psi.) ASME Boiler Code (Includes 1947 Revisions)

Specification ASME	(ASTM)	Grade	Spec. Min. Tensile	Notes	For Metal Temperatures in °F. Not Exceeding: —20 to 650	700	750	800	850	900	950	1000	1050	1100	1150	1200
					Carbon Steels											
SA-30	(A-30)	Flange	55,000		11,000	10,400	9,500	8,000	6,300	....	....	....	....	....	....	....
SA-30	(A-30)	Firebox, Grade A	52,000		10,400	9,900	9,200	7,700	6,100	4,400	2,600	1,350	....	....	....	....
SA-30	(A-30)	Firebox, Grade B	48,000		9,600	9,300	8,750	7,250	5,900	4,400	2,600	1,350	....	....	....	....
SA-89	(A-89)	A	45,000	a	9,000	8,800	8,400	6,900	5,700	4,400	2,600	1,350	....	....	....	....
SA-89	(A-89)	B	50,000	a	10,000	9,600	9,000	7,500	6,000	4,400	2,600	1,350	....	....	....	....
SA-129	(A-129)	..	44,000		8,800	....	....	....	....	....	....	....	....	....	....	....
SA-201	(A-201)	A	55,000		11,000	10,400	9,500	8,500	7,200	5,600	3,800	2,000	....	....	....	....
SA-201	(A-201)	B	60,000		12,000	11,400	10,400	9,100	7,400	5,600	3,800	2,000	....	....	....	....
SA-212	(A-212)	A	65,000		13,000	12,300	11,100	9,400	7,600	5,600	3,800	2,000	....	....	....	....
SA-212	(A-212)	B	70,000		14,000	13,300	11,900	10,000	7,800	5,600	3,800	2,000	....	....	....	....
SA-285	(A-285)	C	55,000	a	11,000	10,400	9,500	8,000	6,300	4,400	2,600	1,350	....	....	....	....
					Low-Alloy Steels											
SA-202	(A-202)	A	75,000		15,000	14,100	12,400	10,100	7,800	5,600	3,800	2,000	....	....	....	....
SA-202	(A-202)	B	85,000		15,000	14,100	12,400	10,100	7,800	5,600	3,800	2,000	....	....	....	....
SA-203	(A-203)	A	65,000		13,000	12,300	11,100	9,400	7,600	5,600	3,800	2,000	....	....	....	....
SA-203	(A-203)	B	70,000		14,000	13,300	11,900	10,000	7,800	5,600	3,800	2,000	....	....	....	....
SA-203	(A-203)	C	75,000		15,000	14,100	12,400	10,100	7,800	5,600	3,800	2,000	....	....	....	....
SA-204	(A-204)	A	65,000		13,000	13,000	13,000	12,500	11,500	10,000	8,000	5,000	....	....	....	....
SA-204	(A-204)	B	70,000		14,000	14,000	14,000	13,500	12,000	10,200	8,000	5,000	....	....	....	....
SA-204	(A-204)	C	75,000		15,000	15,000	15,000	14,400	12,700	10,400	8,000	5,000	....	....	....	....
SA-225	(A-225)	A	70,000	b	14,000	14,000	14,000	....	....	....	....	....	....	....	....	....
SA-225	(A-225)	B	75,000	b	15,000	15,000	15,000	....	....	....	....	....	....	....	....	....
					Medium- and High-Alloy Steels											
SA-240	(A-240)	A	70,000		14,000	14,000	14,000	12,800	9,500	6,750	4,000	2,400	....	....	....	....
SA-240	(A-240)	B	70,000		14,000	14,000	14,000	12,800	9,500	6,750	4,000	2,400	....	....	....	....
SA-240	(A-240)	D	70,000		14,000	14,000	14,000	12,800	9,500	6,750	4,000	2,400	....	....	....	....
SA-240	(A-240)	S	75,000	c, d	15,000	15,000	14,600	14,300	14,000	13,400	12,300	10,000	8000	6000	4600	3600
SA-240	(A-240)	M	75,000	c, d	15,000	15,000	14,600	14,300	14,000	13,400	12,600	11,200	9000	7000	5300	4000
SA-240	(A-240)	T	75,000	d	15,000	15,000	14,600	14,300	14,000	13,400	12,300	10,000	8000	6000	4600	3600
SA-240	(A-240)	C	75,000	d	15,000	15,000	14,600	14,300	14,000	13,400	12,300	10,000	8000	6000	4600	3600

[a] Flange quality not permitted above 850°F.

[b] Between temperatures of 750 to 1000°F., the stresses given herein for killed carbon steel, Specification SA-212, Grade B, may be used until high-temperature test data become available

[c] No allowance has been made for corrosive action in the allowable stress given. Carbide precipitation in service is also to be expected at temperatures above 750°F

[d] The code also assigns allowable stresses up to 1500°F. for Grades S, C and M, and up to 1400°F. on Grade T.

GENERAL

Carbon steel materials covered by code specifications which are not included in these tables are limited to use at temperatures of from —20 to 650°F.

Below the creep range, the allowable stress in wrought materials is one fifth of the ultimate; in cast materials, it is one-fifth of the ultimate multiplied by the applicable quality factor for design purposes.

Any material in this table may be used at temperatures below —20°F. provided it complies with the impact test requirements specified in the code. The allowable stress shall be that given for room temperatures in the table.

1944 have not been readjusted to meet the stress-rupture criterion.

"In the choice of stresses in the range when a percent of tensile strength or yield strength governs, it is presumed that materials will be no better than given in the specifications and no credit is allowed for any improvement in tensile properties by special heat treatment.

"In the transition range between where 20% of the tensile strength governs and where 80% of the stress to produce a creep rate of 0.01% per 1000 hours governs, allowable working stresses shall not exceed 50% of the yield strength for 0.2% offset.".

Allowable stresses do not at present completely define safe loading. Heat transfer stresses in boiler and superheater tubes or other equipment on long cycles of operation are largely ignored, so long as the maximum metal temperature controls the design. Present stress levels and design details and rules apparently are adequate for a reasonable degree of cyclic loading; for extreme degrees of such loading, lower stresses, refined design and, in particular, the highest quality fabrication and examination are essential. It is generally recognized that materials and joints must possess a certain ability to absorb energy and to deform plastically under actual stress conditions. Ship and large pressure vessel failures in recent years have emphasized the hazards of this problem. For low-temperature service below —20°F. the ASME Unfired Pressure Vessel Code, at present, requires that all materials and welds be impact tested. The applicability of the arbitrary dividing line of —20°F. for all materials is currently under study.

Allowable stresses in the API-ASME Unfired Pressure Vessel Code are basically the same as permitted for construction under the ASME Alternate Rules with certain exceptions which are now the subject of study and which will probably be reconciled in future editions. The more important of these are as follows: the stresses for castings include a casting quality factor and the basic values are not identical with those given for wrought material of the same analysis; the stresses for some of the materials with high specified minimum tensile strengths are not based on annealed properties; the stresses for carbon steels above 650°F. are arbitrarily based on a proportion of the specified minimum ultimate strength at room temperature except for A212 plate for which the allowable stresses above 850°F. are decreased to the level of a 55,000 psi. strength steel; no distinction is made between killed and rimmed carbon steel, the same stresses being allowed for both; and the stresses for carbon steel above 950°F. exceed the stress to cause 0.01% creep in 1000 hours.

Figure 2 shows curves of the ASME and API-ASME Code allowable stresses together with typical tensile, creep and stress-rupture curves for a killed carbon steel.

When the strength of the vessel cannot be accurately calculated, the codes provide for proof tests (see Inspection).

Design Formulas

Formulas based on the theory of elasticity are used for the entire temperature range, although it is realized that at high temperatures, plastic flow or creep proportional to stress tends to equalize stress distribution. The margin is in the direction of safety with higher temperatures. The simple stress theory is employed, ignoring interaction of strains along other axes, which is probably the best compromise since the strain energy, maximum strain or other criteria for predicting yielding are as yet insufficiently explored for correlation with high-temperature behavior.

For shells and spheres, approximations of the Lame Formulas are used in both codes and for cones a similar formula is used. For ellipsoidal or dished heads the membrane formula is used directly or, with test and experience data, to arrive at factors to be used in simplified formulas. In this connection, except for a few pressed heads, all heads are two radii (torispherical) in shape with high stresses at the torus—sphere intersection, which are lowered as yielding under hydrostatic test pressure permits ellipsoidal contour to be approached.

For flat covers the thin plate formula is used with a varying constant to take care of edge fixation and the particular detail used; in the case of bolted covers with inside gaskets, there is an added factor for the edge moment due to the gasket reaction. Bolted flange rules (inside gasket facing) which evaluate the distribution of moment between the flange ring and the hub are given in organized

form, and involve the assumption that the bolt load is that required for a tight joint increased by one-half the strength of any excess bolt area, as a protection against overtightening. For simplicity, this formula ignores direct and discontinuity pressure effects; it also provides for longitudinal bending stresses 50% above the nominal allowable design stress provided the average of the flange and hub stresses is within the code value. With the additional stress imposed by direct end pressure the total hub stress may reach twice the nominal design value. Localized stress conditions of this and higher orders are regularly encountered in vessels, for example, in the knuckles of minimum code heads, around openings, etc. The averaging of flange and hub stresses is justified since the combined structure will not yield until both are overstressed.

Code rules permit specified small openings without checking for strength on the basis that the coupling or nipple and weld will always provide sufficient strength for the weakened area so that stress intensification will not be excessive. Elsewhere reinforcements within a prescribed area must essentially replace the metal removed, and welds must provide comparable strength. Analysis and tests are under consideration to determine more effectively the relation between location and effectiveness of reinforcements and attachment welds, and the amount required to keep stress intensification within prescribed limits. More attention should be paid to normal and bending stresses imposed on nozzles by piping, and reinforcement details best suited to such loading; also to multiple or numerous openings where effects overlap, to openings large in proportion to the vessel diameter, and to openings located in areas of contour changes such as in the knuckle area of heads.

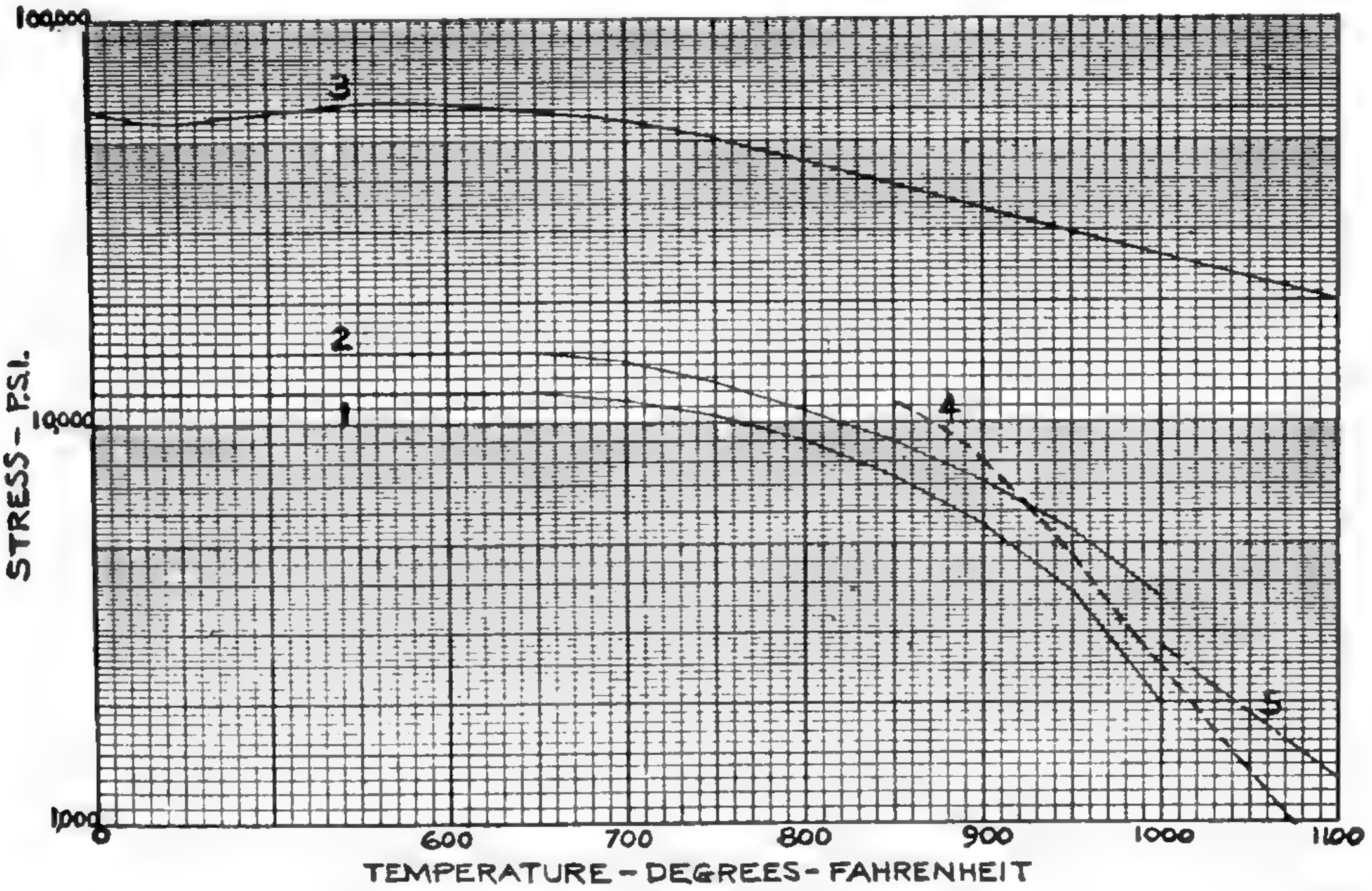


Fig. 2.—ASME and API-ASME Allowable Stress for Killed Carbon Steel (ASTM A-201 Gr. B 60,000 Min. T.S.) Together with Typical Short Time Tensile, Creep and Stress-Rupture Curves

1, Allowable working stress, ASME Code; nominal safety factor 5. *2*, Allowable working stress, API-ASME Code; nominal safety factor 4. *3*, Short-time tensile strength; *4*, Creep strength—rate, 1% in 100,000 hr.; *5*, Stress to rupture in 100,000 hr.

Some acceptable types of arc- and gas-welded nozzles and other connections to pressure vessels are shown in Figs. 3 and 4. These figures are reproduced from the ASME Code. Figure 4 illustrates a type of nozzle detail to be inserted in an opening of the shell and attached with a double welded butt joint. Radiographic

examination of the weld can be made readily with this type of nozzle. This is a desirable design but unfortunately is very seldom used since other types of nozzle attachments are cheaper at the present time, and will remain so until machining of this nozzle is perfected.

Under external pressure, stability must also be considered. Rules appear in both pressure vessel codes for checking against such collapse. For simplification maximum possible stiffener loading is assumed so that stiffener size can be obtained from a chart. Similarly, longitudinal shell bending at stiffeners is taken at a maximum which again implies infinitely rigid stiffeners so that maximum pressures can be charted.

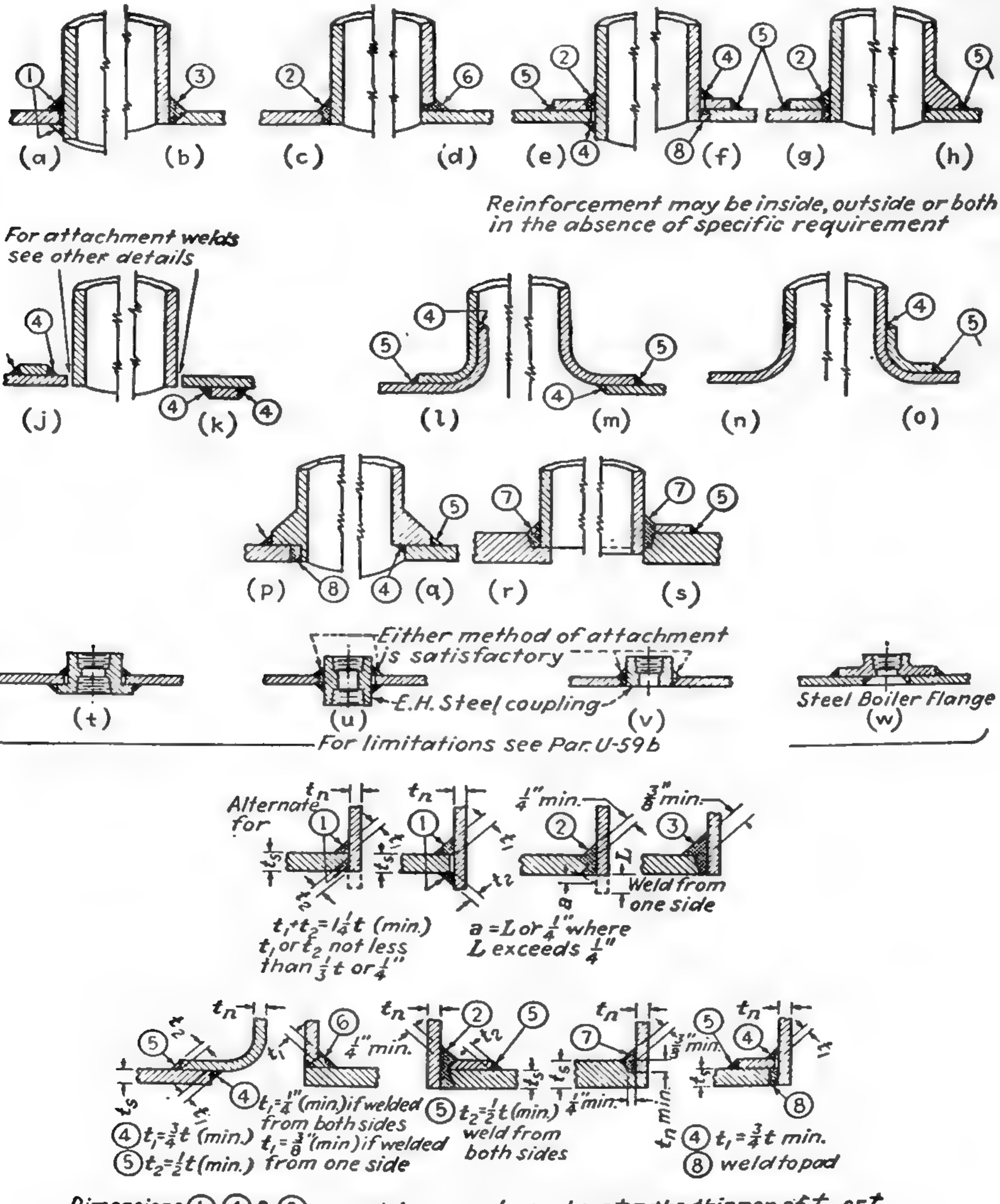


Fig. 3.—Some Acceptable Types of Arc-Welded Nozzles and Other Connections

All of the foregoing is concerned with principal direct or bending stresses which result directly from pressure, bolt loading or other external sources. The single exception is the external pressure vessel where secondary stresses result from the stiffener resisting inward movement of the shell. Similar axially symmetrical discontinuity is encountered in any vessel where members or sections are joined or at intersections of shapes of revolution having unequal membrane displacement. Sharp intersections, such as between a shell and cone, are an example. The unbalanced radial component of the longitudinal membrane stress in the cone sets up a ring loading at the intersection causing localized direct and bending stresses which may be excessive. Non-symmetrical bending piping stresses (in so far as the vessel axis is concerned) appear around nozzles due to the difference in longitudinal and circumferential stress and also to direct or bending loads, around lugs and saddles, around ties or staybolts and in general at all localized loads. There is need for a recognized limit for such stress in comparison with the so-called allowable stress, which as used in code rules governs principal stresses only. This limit would necessarily differentiate between those cases where yielding produces stronger or weaker contours, between internal and external loading, between direct versus bending effects and give due significance to location and extent. Such questions are being actively studied by the Design Division of the Pressure Vessel Research Committee of the Welding Research Council.

Welded Joints

Butt joints welded from both sides offer greatest assurance of uniform or complete bonding and should be used where maximum strength is required or where shock, fatigue or plastic deformation such as creep may occur. Equally satisfactory is the single groove weld made against a backing, which is subsequently removed and the welding surface repaired if necessary. Where the backing is not removed, an unknown root condition exists which may initiate failure under repeated loading particularly on longitudinal welds. However, such welds are permitted under the codes on the same basis as welds made from both sides. Other types of joints in order of decreasing joint efficiency are the butt joint welded from one side only, the lap joint fillet welded on both sides, the lap joint with a single fillet weld and plug weld and the lap joint with a single fillet weld only. Their assigned joint efficiencies in proportion to butt joints welded from both sides can be justified only on the basis of static, non-fatigue comparison since inadequate fusion and unknown root conditions are inherent to groove welds made from one side only and to fillet welds, and vessels fabricated by such welding are usually for less critical service.

The codes in some cases permit girth seam welding to be inferior to that on longitudinal seams. However, a word of caution is necessary. Although the longitudinal membrane stress in a cylinder is only one-half the circumferential stress, a girth seam carries the full circumferential stress in cross section and may be subject to high secondary bending stress depending upon its location, i.e., proximity to end flanges, nozzles, heads and appurtenances. For best construction, all seams should be of equal quality.

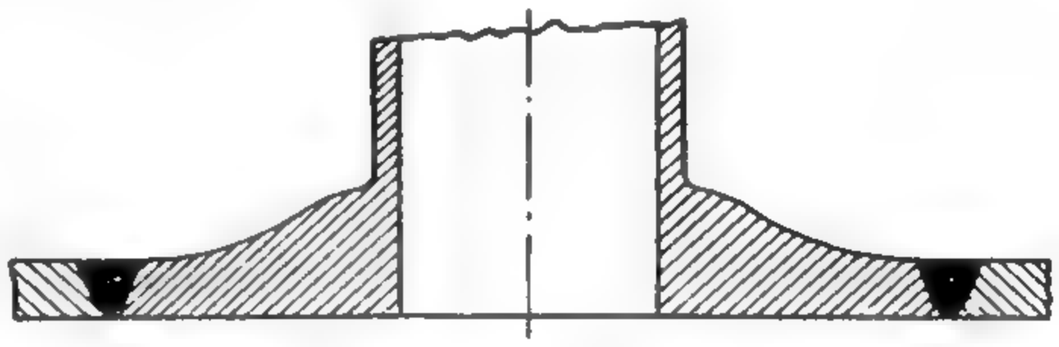


Fig. 4.—Inserted Type Nozzle

The API-ASME *Code for Unfired Pressure Vessels for Petroleum Liquids and Gases* contains a formula for evaluating permissible shear or tension in plug welds as well as shear and tension loading factors for groove and fillet welds as a function of the relative weld-load direction for use on nozzle attachments, plugs and similar parts.

Welded Joint Efficiencies—Construction Factors—Premium Inspection

The ASME Code gives joint efficiencies (or permissible stresses for U-70 construction) which involve all considerations. The API-ASME Code final joint efficiency combines the welded joint efficiency with construction factors for plate quality and for radiographic examination and stress relief. These are noted in Table 3.

Plate quality construction factors are discussed under Materials, and radio-

graphic examination under Inspection and Fabrication. The contribution of non-destructive detection of cracks, etc., to increased safety under shock or repeated loading cannot be over-emphasized and code rules should be extended to encourage their more generous use. Greater premium for overall examination would appear to be justified, with spot examination required for intermediate design efficiencies and with lower allowable stresses assigned where there is only visual examination.

Stress relief is discussed in detail under Fabrication. Its contribution to safe construction in the case of non-air-hardening steels is debated mainly on the basis that many unstress-relieved vessels have given many years of satisfactory service. As already pointed out, reasonable safety in pressure equipment is associated with complete, not average, safety. Admitting that adequate stress relief is commonly effected on thin vessels by the code hydrostatic test, nevertheless the possibility of opening up or initiating flaws in highly stressed areas cannot be ignored. With more severe service the issue is clearcut in favor of initial stress relief before the application of pressure or other loading in appreciable magnitude. To this must be added the greater freedom from accelerated corrosive attack in heat-affected zones or the general hazard of stress corrosion.

Supports

Vessels are supported in many ways all of which introduce localized effects, and the resulting direct, bending or secondary stresses should be explored and maintained at the level established directly or indirectly for similar stress.

Direct loading equally distributed around the circumference is most favorable, the nearest approach for vertical vessels being skirt supports which when fillet welded to the shell introduce bending similar to a lap girth joint or when welded to the knuckle portion of the head introduce bending in proportion to the load component normal to the surface at the point of attachment. Such bending stresses are at a minimum when a generous knuckle radius is used and when the mean diameter of the vessel shell and skirt coincide. Comparably favorable design is possible with ring girders or band reinforcings which are used to spread the concentrated support reactions and minimize their effect on the remainder of the vessel. Next favorable would be infinitely rigid legs or combined lugs and supports which would take the total bending moment caused by the vessel weight without rotation. In practice, most legs or the beams of supporting structures are much less rigid than the vessel shell, which, therefore, carries essentially the entire bending effect. Spreading the area of attachment and local reinforcement reduces induced stresses. For horizontal vessels, lugs and hangers or legs are sometimes used, but more often saddles, usually free but sometimes integral with the shell are employed. The bending moment from lugs and legs can be minimized by locating the center-line of the support to coincide with the mean radius of the shell at the point of tangency, and further by locating the supports at a head or other point of enhanced circumferential stiffness. Properly fitted saddles cause longitudinal bending along the curved edges, and circumferential bending at the ends. The former is controlled by saddle area and arc, the latter by saddle width and arc, pincipally the arc, so that a 120 deg. minimum angle is usually necessary unless shell thickness in excess of pressure requirements is available.

When supporting vessels containing fluids at high temperatures, adherence to surfaces of revolution is most effective in minimizing the effect of temperature differences introduced by heat loss at the supports. Due to the continuous metal structure, insulation is not very effective in controlling temperature differences, serving rather to equalize conditions around the circumference. Accordingly, skirts are the preferred construction, having the added advantage of permitting control of temperature at the steel or concrete supporting structure so that movement or damage will not result. Surfaces of revolution can absorb axial temperature gradients without stress except for end restraints, which are proportionate to the gradient; while flat plates, etc., are completely restrained with maximum stress. This accounts for distortion and cracking in lugs and their attachment welds, so that even local attachments are preferably made of pipe. For service at high temperatures, horizontal vessels are preferably avoided, or, when necessary,

rollers, hangers or similar construction to permit free axial expansion should be used.

Comparison of Design Requirements of the ASME and API-ASME Codes.

Table 3 presents in tabular form a comparison of the principal design requirements of the ASME Unfired Pressure Vessel and API-ASME Unfired Pressure Vessel Codes. The reader is cautioned to consult the Codes directly for specific information, since a tabulation such as this cannot be all inclusive.

FABRICATION

General

While welded vessels, particularly those of light wall thickness, may be fabricated with very little equipment, specialized equipment, skilled workmanship and proper organization are necessary if welds are to be favorably located, distortion, fit-up and mechanical working controlled and residual stresses minimized.

Plate Layout and Preparation for Forming

The designer establishes the plate layout for a vessel on the basis of considerations of minimum welding, avoidance of seams at connections, shop equipment limitations and overall economics (welding cost vs. plate extras). To minimize accumulation of tolerances on measurements, a base reference plane should be established (usually at the point of support on vertical vessels and at an arbitrary location for horizontal vessels) and all nozzles, manholes and other attachments are located from this single plane. In laying out plates, the squareness should be checked and allowance made for weld shrinkage. Also when hot forming or high-temperature treatment is involved, allowance should be made for oxidation loss. Light-walled vessels are often laid out with openings cut in a flat plate. Complex or heavy-walled vessels usually require layout on the fabricated cylinder before heads are attached.

Single plate courses are generally chamfered before forming for welding. On hot-formed heavy plate, the circumferential edges are sometimes machined after forming to improve fit-up to adjacent courses. On multiple plate courses or large spun heads, two or more plates are often welded together before forming. For pressed shells successive increments are closely marked, so that with each operation, twisting will be avoided.

Plates rolled before chamfering should be free of shear pinch, cutting irregularities or other defects which might propagate during bending. Scarfed edges must be uniform, smooth and square if satisfactory welded construction is to be obtained.

Forming

Forming by pressure, not blows, is the accepted practice to avoid hammer marks and accompanying residual stress. In general, cold forming is employed within the capacity of available equipment and has the advantages of closer dimensional tolerances, absence of oxides, lower cost, and less expensive and longer lasting dies. Hot forming, in addition to requiring lower power as a result of reduced yield strength, permits more severe working in a single operation, and with sufficient temperature removes grain distortion by recrystallization and also, with uniform cooling, effects stress relief. The limits for deformation in one operation of hot or cold forming are not well established and are reduced with size and complexity much below values obtained on relatively small test specimens. Cold work raises the yield point, reduces the ductility and shock resistance, increases susceptibility to aging and apparently increases the hazard of welding cracks. Stress relief improves ductility and shock resistance. Complete heat treatment is advised after severe cold work to restore normal structure. In heating for forming, temperature and time at temperature must be controlled to avoid grain coarsening and oxidation. Local heating and forming usually involve possible flaw propagation due to temperature and forming load stresses, and distortion. It also results in residual stresses. Most of the operations mentioned in the following can be performed either hot or cold.

Flat plates are usually made cylindrical by means of bending rolls; presses and press brakes are also used. In bending a cylinder on rolls the area adjacent to the longitudinal edges is not curved to the required degree. To overcome this condition, the longitudinal edges of the flat

plate are pressed to curvature either on a press or in the rolls working over a heavy plate which has the desired radius. Circularity may be further improved by rerolling after longitudinal welds are completed, particularly if done hot.

Cones of small included angle are often formed on cylinder bending rolls, and with rerolling after forming, steeper cones are satisfactorily shaped. As the cone included angle increases, use must be made of cone rolls, pressing or spinning (similar to heads). Torii may be assembled from pressed sections separate from the cone or shell plates, or from sections integral with the cone. Lately equipment has become available for bending large diameter cylinders, similar to pipe bends. Spheres are usually assembled from pressed sections, although in smaller sizes, hemispheres are shaped by spinning (similar to heads).

Small diameter thin heads are often stamped, while those of somewhat larger size are cold pressed or hot pressed. Fabrication shops often form large heads for field-fabricated vessels or two-piece heads for smaller vessels on so-called sectional flanging and dishing presses.

Special forming operations required for various parts of pressure vessels are: fluing for integral nozzle construction or manholes, upsetting of plate edges, vanstone laps for furnaces and glass-lined vessels, swaging on double shell (jacketed) vessels, corrugating flues, etc.

Preparation for Welding

Surfaces should be examined for laps, slivers, rolled-in scale, pits, etc., and both the surface and edges of plates visually inspected for evidence of laminations. Plates must be square and to dimension. Adjustment of circumference or compensation for irregular edges by variation in root opening should be avoided. Proper allowance must be made for weld shrinkage.

Welding grooves, wherever possible should be machined (planed or milled in flat; turned or milled on cylinder girth seams) or machine oxygen cut to provide a straight, uniform, smooth contour for welding. On sheared edges, sufficient metal should be removed in subsequent scarfing to assure freedom from shear drag and tears. Direct bevel shearing of scarfed edges is not considered good practice. Welding edges may also be formed by cold or hot rolling the plate edges to the desired shape.

Irregular edges are chamfered by chipping or manual or portable machine oxygen cutting, and should be carefully laid out using templates wherever possible, particularly on nozzle openings. Groove contours should be carefully and continuously checked with gages, and inaccuracies corrected by grinding to remove excess metal, while excessive width calls for building up and stress relieving the deficient area, subsequently chipping or grinding to contour.

On air-hardening materials, with carbon over 0.30%, or low-alloy steels, or on very thick carbon steel, oxygen grooving is not desirable since rapid cooling hardens the edge and, at locations where the cutting operation is started, cracking due to thermal shock may occur. Where such material is shaped by oxygen cutting the hardened edge to a depth of $^1/_{16}$ to $^1/_8$ in. should be removed by grinding and the possibility of thermal shock reduced by preheating.

Some conventional types of weld grooves are shown in Fig. 5.

Assembly

The economic advantage of employing surfaces of revolution in the construction of pressure vessels, with principal stresses as direct tension or compression, has been pointed out. Deviations from true shape superimpose bending stresses on direct stress, with possible yielding under test or in service. These deviations occur as non-uniformity of radius at a cross-section, or as random interruptions (not axially symmetrical) in a pressure shell and are the result of inaccurate forming and assembly, or welding shrinkage and non-uniform heating or cooling during heat treatment. Plastic flow, usually of a low order, will correct faulty curvature, except in areas where the radius changes abruptly, flat areas of appreciable width and areas of reverse curvature, where considerable yielding may be required. Such yielding continues until the affected portion assumes a stronger shape or, in extreme cases, to failure. In any event the excepted cases constitute weakness against shock or fatigue loading.

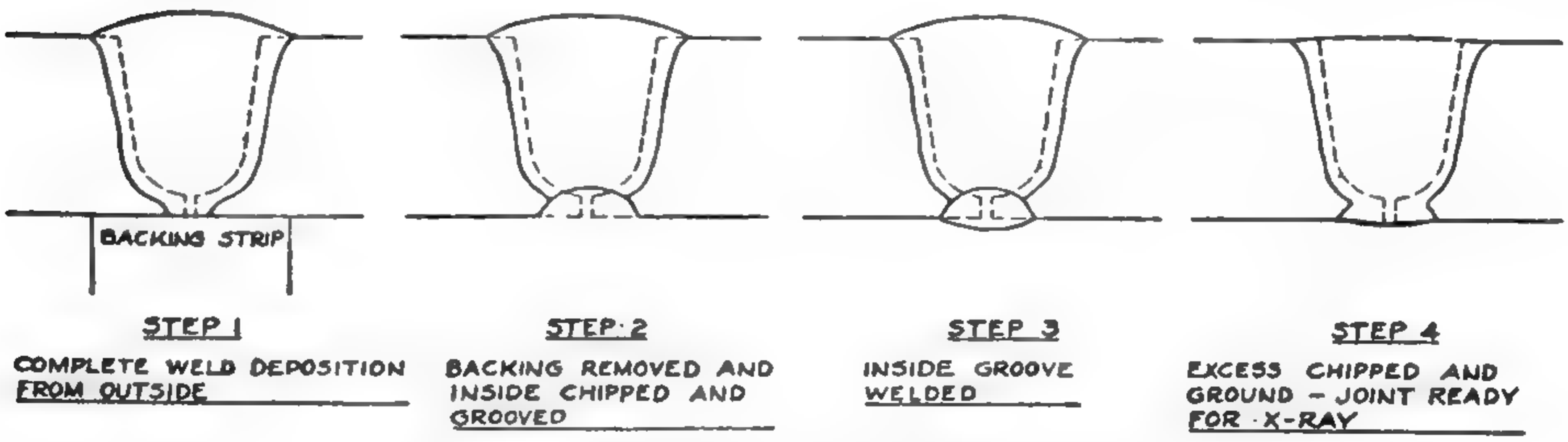
True circularity at the plate edges will reduce the plastic deformation imposed on

the heat-affected zone and deposited metal of longitudinal welds. Minimizing radial shrinkage by welding technique and rerolling after longitudinal welds are completed will be similarly beneficial and will provide reasonably true cylinders for matching up at girth seams. Distortion as well as residual stress are further reduced by planning the assembly of each pressure vessel so that welds can be made under a minimum restraint. For example, light-walled vessels are often completely assembled and tacked so that welding can proceed from seam to seam, resulting in restraint against free circumferential movement when the longitudinal welds are made and in higher residual stress at

taining correct root spacing and alignment of edges. Some of these are tack welded to one or both plates, others employ friction from the loading of bolts or wedges. Tack welds or clamps are usually removed as welding is sufficiently completed. For alignment of girth seams, the shell courses are lined up by clamps although internal spiders at the end of each course are much more effective in minimizing offset. For proper fit-up at heads, the heads and shell must have the same circumference. Also the head flange thickness must be checked for excess thickness.

Localized distortion should be corrected by jacks and struts, instead of hammer-

a. Some Conventional Types of Welding Grooves



b. Steps in Welding Process—Single U Groove

Fig. 5.—Typical Grooves for Welding Pressure Vessels

weld intersections. Better quality fabrication, essential to heavier wall construction, requires longitudinal welds to be completed in individual courses, usually followed by stress relief or hot rerolling before girth seams are deposited, thus eliminating any possible accumulation of weld stresses at intersections. Radiographic examination of longitudinal seams, when required, is desirable before welding the girth seams so that any necessary repairs can be made under most favorable conditions.

Plate edges at longitudinal seams are carefully aligned and tacked, or to avoid possible flaws at tack welds, various types of clamps are used which assist in maintaining and local heating. However, in the interest of economy and safety in service, distortion should be prevented wherever possible. Before jacking, and in general where welding or other operations have accumulated stress or noticeable distortion, stress relief is necessary. Such intermediate stress relief need not adhere to code requirements as to soaking time or heating or cooling rates, since partial stress relief usually is sufficiently effective. Out-of-round tolerances are specified in both the ASME and API-ASME Codes as well as tolerances for plate misalignment at seams.

The vessel shell should be carefully prepared with accurate holes for nozzle

attachments and integral or loose reinforcing pads should fit the shell surface as accurately as possible. Since most nozzle welds are between rigid components, a backstep sequence is often employed to minimize stress accumulation, and the peening of each weld layer is sometimes considered effective in further reducing locked-up stress.

Chipping, Grinding and Oxygen Gouging—Repairs.—Finished weld quality is greatly dependent on properly cleaning and chipping each layer before successive layers are deposited and the ability and experience of personnel performing these operations should be equal to that of the qualified welders with whom they are teamed. Such preparation is performed by chipping, grinding and oxygen gouging with emphasis on smooth, uniform contour and thorough removal of questionable areas.

Satisfactory chipping necessitates tools of adequate material properly heat treated and ground. Chisels and gouges must be of proper width and shape for the size and shape of the groove. Expert chipping is essential for quality welding and is of inestimable value in minimizing repairs. Grinding is mainly employed as an adjunct to chipping, particularly in smoothing out or blending contours. It is also useful in restricted areas being probed for defects, in finishing welds where the reinforcement is to be removed and in removing undercuts.

Oxygen gouging is, to an even greater extent, dependent on the ability of the operator if uniform, satisfactory results are to be obtained. It is well adapted to preparation of complete seams or extensive areas for butt welding and is used to gouge out defects in the repair of welds. However, oxygen gouging has been somewhat limited in use for repairs due to its tendency to propagate cracks.

With radiographic examination, repairs become an important factor in the quality and economy of the finished weld. Procedure control, equipment maintenance and continuous checks on operators are necessary to minimize the necessity for repairs. Experienced interpretation of radiographs and skilful exploration of the selected areas for location of the defects will limit the extent of the repairs, and therefore will aid in preserving the original contour of the weld.

Welding Processes

General.—Arc-welded joints of high quality are easily secured by many different processes permitting selection to suit the nature of the work.

All of the present-day welding processes are used to varying degrees in the construction or repair of pressure vessels, boilers and their attachments. Fundamentals and techniques are covered in Chapters 4 to 22; and the following comments cover applications, limitations and details.

Metal-Arc Welding.—The shielded metal-arc welding process using multiple layers, is predominantly used in pressure vessel fabrication, particularly in heavy-walled construction.

The best accepted practice in shop fabrication of pressure vessels is the use of the E6020 and E7020 or E6030 and E7030 electrodes in the flat position, which yield the highest quality deposit with the greatest deposit rate. See Chapter 10 for further information on the fundamentals of this process.

Submerged Arc Welding.—This process automatically feeds a bare electrode through a powdered flux, which under the heat of welding produces a slag protection for the molten metal and covers the arc. The process is rapid and has been used with two or more passes in plate thicknesses of 2 in. or more. The mechanical properties reported for welds made by this process satisfy the various code requirements for high-tensile, 70,000 psi. plate as well as for 55,000 psi. plate. With the usual heavy passes, there is a tendency to draw out plate defects into the weld, so that fully-killed steel is generally preferred.

Submerged arc welding may be used for multilayer welds also, and some fabricators use it in this manner for heavy plate sometimes limiting each pass to approximately $^1/_4$ inch. This serves to break up the pronounced cast structure, with its possible weakness against shock or fatigue, which is characteristic of the thick layers. See Chapter 13 for information on the fundamentals of this process.

Atomic Hydogen and Inert-Gas Metal-Arc Welding.—Atomic hydrogen and inert-gas metal-arc welding find their principal use on high alloy steels, nonferrous alloys and for special applications where

increased cost is offset by other considerations.

Shielded Carbon-Arc Welding. — Shielded carbon-arc welding due to its slow speed and high heat input, affords good control of the weld dimensions and penetration and finds application on light-walled carbon and alloy steel vessels. Shielded automatic carbon-arc welding produces welds conforming to highest quality code construction and, contrary to popular impression, the carbon content of the weld is reduced rather than increased provided straight polarity is used. The practical thickness limit is about $^3/_4$ in. and in this thickness the weld may be made in two passes, one from each side. See Chapter 9 for further information on the fundamentals of this process.

Oxy-Acetylene Welding.—Oxy-Acetylene welding may be used in the construction of pressure vessels of limited thickness, and good quality weld metal is obtained by properly trained operators. Gas welding is particularly suitable for the butt welding of small tubes and pipe and, with skilled manipulation of the welding torch and proper design of the welding groove, thorough penetration may be obtained at the root of the weld without the use of a backing ring. Oxy-acetylene welding supplies its own preheat and residual stresses may therefore be lower but distortion generally is greater than for metal-arc welding. See Chapter 5 for further information on the fundamentals of this process.

Resistance Welding.—Spot, seam and flash welding are used in superheater and flanged nozzle fabrication, the attachment of liners, also girth seams and the progressive welding of longitudinal seams on small non-code pressure vessels. Where a large number of similar parts is to be welded, these processes offer the advantages of economy and speed. For pressure vessel application, they are generally limited to relatively small diameters. See Chapters 16 and 17 for further information on the fundamentals of these processes.

Brazing.—Brazing finds only limited use on pressure vessels. It is confined mainly to the construction of small thin-walled vessels which are production items for mild service conditions. Section VIII *Unfired Pressure Vessels*, of the ASME Boiler Code, contains rules for brazed vessels of ferrous materials but not for nonferrous vessels. Under these rules many small air tanks, $^5/_{16}$ in. or less in thickness with diameters to 24 in., may have a brazed longitudinal joint. The brazing is generally performed in a furnace using a lap joint with a minimum lap of eight times the plate thickness. Since the circumferential welds of the head are arc welded with steel filler metal, it is necessary to arc weld a short length at each end of the brazed seam prior to brazing. This also aids in holding the shell for the brazing operation. For more detailed information on brazing see Chapter 22.

Qualification of the Welding Procedure and Welders

In order to check the adequacy of the joint details and technique, the various codes and the American Welding Society have adopted standard tests for qualifying welding procedures and welders. The codes have established certain minimum requirements, but in keeping with the manufacturer's responsibility, it is expected that he will conduct such additional tests as may be necessary to assure welds of the required quality.

The ASME Boiler Code for U-69, U-70 and U-201 vessels specifies that qualification be in accordance with Section IX of the Code, which essentially follows the American Welding Society's *Standard Qualification Procedure* with modifications to cover certain alloy steels. For U-68 and U-200 vessels and for power boiler drums this same code provides that vessel test plates be made as noted in Table 2, and that the welding and testing of these test plates constitute continuous qualification of the welding procedures and the welders. The API-ASME Code requires qualification of procedure and welder in accordance with the American Welding Society's *Standard Qualification Procedure* and in addition requires a test plate for each vessel or group of small vessels. (See Chapters 45 and 60.)

Neither code as yet contains specific requirements for the qualification of automatic welding. It is recognized that some modification of the present rules for manual welding should be made to establish limitations of the variables which can affect the quality of the finished weld and also to define the oper-

ator and his qualification requirements. In the absence of specific requirements inspection agencies and manufacturers generally apply code rules for manual welding to automatic welding as far as applicable.

Test Plates.—As noted in the preceding section the ASME Code requires a vessel test plate for boiler drums and for U-68 and U-200 vessels; vessel test plates are not required for U-69, U-70 or U-201 vessels. The API-ASME Code requires a test plate for each vessel or group of small vessels. The detail test requirements are summarized in Table 2. The test plate should preferably be welded as a continuation of a longitudinal joint but this is not mandatory.

There is considerable feeling that, if the procedure has been once qualified by adequate tests and the vessel seams are examined by complete or reasonable spot radiographing, vessel test plates could be omitted. Reluctance to accept this stems mainly from the fact that qualification tests are not witnessed by inspectors.

Preheating

On plain carbon steels preheat is generally employed for heavy plate, and many fabricators favor warming up all thicknesses to avoid cracking on material having a high transition temperature (temperature at which large loss of impact resistance occurs). Warming up or preheating of air-hardening materials is essential to avoid thermal shock cracking with starting of the arc or application of the torch. With austenitic steels, opinion is more divided. However, most fabricators employ preheat on thicknesses over $^1/_2$ inch. Preheat temperatures start at 100°F. with a more usual minimum of 200°F. for carbon and austenitic steels, and 300°F. to 800°F. for air-hardening steels depending upon their tendency to air harden and also upon operator comfort, size of electrode used, thickness, etc.

Preheating may be done by gas burners or by resistance or induction heating. Best practice is to bring the entire seam being welded up to the desired temperature with perhaps a slight increase at the point of welding, particularly when using a preheat temperature over 150°F. Highly localized heating may introduce serious thermal stresses and nullify the benefit expected. The heating should be maintained during welding and in the case of the chrome-moly steels (above $^1/_2$% chromium) the weld should not be allowed to cool during welding or until it has received its postweld heat treatment. (See also Chapter 43.)

Peening

Peening produces mechanical working of the weld metal by mechanical blows and is often used on low-carbon steels with beneficial results to control distortion and effect a limited measure of stress relief. It is usually not used on alloy steels which work harden readily.

Peening is generally done with a pneumatic hammer. The tool should be smooth faced. Spherical tips with about $^3/_{16}$-in. radius are sometimes used while flat-faced tools with about a $^3/_8$ in. by $^3/_4$-in. face with edges rounded to about $^1/_{16}$ in. have given good results. Peening is usually not done on the first two root passes or on the cover pass.

The API-ASME Code permits the substitution of controlled peening for thermal stress relief in the case of large field-assembled vessels. However, it is considered by some not to be an equally effective substitute. (See Chapter 43.)

Finishing of Welds

Welds not subject to radiographic or other quality examination are generally left as deposited. The weld reinforcement (approximately $^1/_8$ in.) should be kept within the limits of the regulations and the weld should merge smoothly into the base plate to avoid stress concentrations at the edges of the weld. When the welds are to be radiographed, surface irregularities which may interfere with proper interpretation of the radiographs must be removed and it is recommended that the reinforcement on both sides of the weld be chipped, and ground substantially flush with the surface of the plate. In addition to aiding interpretation of films, such finishing greatly improves operating stress conditions. The ASME Code permits an increase of 5% in joint efficiency for construction conforming to Pars. U-68, U-200, P-101 and P-102 requiring removal of reinforcements. When finishing welds flush it is important to grind so as to eliminate the slight sharp corner which may be present at the toes of the weld. This is sometimes not done because of the danger of reducing the basic wall thickness.

Welds which are to be inspected by magnetic powder or penetrant oil should be ground, if the inspection is to produce optimum results.

Relief of Residual Stress

Residual stress refers to the stress existing in an assembly which is free from external load; the term *stress relief* may be applied to any means for substantially reducing such stress. It may be thermal, mechanical or a combination of both.

Ostensibly the most important reason for stress relieving is to reduce residual stresses sufficiently so that, in combination with service stresses, the reduced residual stresses cannot cause the brittle failures which might otherwise occur. Stress relieving is commonly thought to be particularly valuable for vessels subject to cyclic loading. Thermal stress relief is known to greatly reduce the hazards of stress-corrosion and corrosion-fatigue.

For adequate stress relief, it is necessary that a vessel be relatively free to adjust itself under the action of the residual stresses, since retained strain can be reduced in magnitude only by plastic flow. This reduction can be accomplished mechanically by superimposing additional strain through external or internal loading and/or thermally by reducing the yield strength of the material. The modulus of elasticity and yield strength of most materials decrease with increasing temperature; only when the latter decreases more rapidly than the former is stress relief effected by temperature change alone. However, when the influence of time is combined with that of temperature, plastic flow occurs at stresses well below the yield strength due to creep or relaxation, the rate of flow being a function of both the stress level and time. Moderate heating sometimes produces a greater amount of stress relief than can be explained by decreased yield strength/modulus ratio or by relaxation.

The usual stress relief temperatures for carbon steels vary from 1100 to 1250°F. although lower stress-relief temperatures down to 900°F. are used where higher temperatures are not feasible. Corresponding soaking time is 1 hr. per in. of thickness at 1100 to 1250°F. and 10 hr. per in. at 900°F. Typical stress relieving temperatures and times for steels are given in Table 7.

The wide range shown for 18% Cr–8% Ni covers, at the higher temperature, the view of those who insist that adequate reduction in yield strength and relaxation requires temperature of this magnitude, while the more often used lower temperature is justified by others by the fact that cold work is rapidly removed at this lower figure. Faster heating and cooling rates could logically be used for simple vessels, while complex vessels with many manholes, nozzles, etc., can withstand little non-uniformity in temperature without yielding. For heavy thicknesses or complicated assemblies, one or more intermediate stress reliefs are often used to avoid possible failure during fabrication.

Table 7—Typical Stress-Relief Heat Treatments

Material	Holding Temperature, °F.	Soaking Time, Hrs./In. Thickness
Carbon steel	1100–1250	1
Carbon–1/2% Mo (0.20% C)	1100–1250	2
Carbon–1/2% Mo (0.35% max. C)	1250–1400	2
2% Cr–1/2% Mo	1325–1375	2
2 1/4% Cr–1% Mo	1350–1400	3
5% Cr–1/2% Mo	1350–1400	3
12% or 16% Cr	1425–1475	2
18% Cr–8% Ni	1200–1500	4–2

NOTE: Heating rates are generally less than 400°F. per hour with less than 200°F. per hour being used for austenitic steels and usually for chrome-moly. and straight chrome steels. Cooling rates are generally not more than 200°F. per hr., with lower values for alloy steels.

Many fabricators have large furnaces permitting stress relief of complete units; large vessels are sometimes heated by the circulation of hot gases from flue gas generators, with or without recirculation, or from burners within the vessel. For long vessels, the codes permit stress relief of alternate halves with prescribed overlap or in sections with local stress relief of final girth welds. Progressive stress relief by moving a vessel through a furnace, or by moving a furnace along a hearth on which the vessel rests, has been used.

Local stress relief is employed where the vessel size is beyond the furnace capacity and is effective in proportion to the application and control details. In addition to greater possibility of uneven

heating, it involves thermal gradients around the boundary of the heated area, which introduce stresses into both the boundary and heated zones. These can be controlled by limiting such heating to complete circular bands of adequate width (minimum 12 times plate thickness) and by avoiding excessive axial temperature gradients by the use of insulation and/or the gradual reduction in heat input, with a maximum gradient of 200°F. along the shell. The ASME Boiler Code at one time contained provisions for stress relief of nozzles by heating a localized area around the nozzle, but adverse experience led to its withdrawal. (See Chapter 43 for a further discussion of stress relief.)

INSPECTION

Purpose

The purpose of inspection is to give assurance of compliance with code and specification requirements, by enforcement and interpretation of such rules in the light of experience beyond that of a single manufacturer. Experienced visual inspection contributes much to safety and can be made more effective when supplemented by other examinations such as radiography, magnetic particle examination, sectioning, fluorescent penetrant oil examination, supersonic and ultrasonic testing and etching. The selection of any method and the extent of its use usually depend on the intended service and individual opinion on the hazards attendant upon undetected flaws.

Visual Inspection

To be effective, visual inspection should be made during all stages of fabrication, particularly welding edge preparation and fit-up, and should also include a check of the materials and design. Sand or shot blasting is an excellent aid in the surface inspection of heavy plate as adhering mill scale often hides imperfections such as scale pits, rough areas or surface laps. Procedure and welder qualifications should be assured and the welding operation carefully observed for proper adherence to the welding procedure. On seams which are not to be radiographed and for all nozzle welds cleaning and chipping should be emphasized, with particular attention to the first layer or root pass. The surface finish of the weld should be checked and areas which might serve as stress raisers such as undercut, overlap or excessive reinforcement should be removed. The appearance of a completed weld yields some information on operator's ability to an experienced inspector, but obviously more than surface inspection is necessary to assure soundness of welds. Observations made during the actual welding are a minimum requisite for reasonable evaluation of weld safety. One of the most difficult decisions for an inspector is what remedial measures to sanction for repairs to correct an unsatisfactory condition, and here he must rely to a large extent on experience and sound judgment, since code rules cannot provide such detail guidance.

Radiographic Inspection

Radiographic examination involves the use of radiation from specially constructed industrial X-ray machines, or the use of gamma rays from a capsule of radium. The processing and interpretation of the photographic films obtained from such examination requires much skill and experience to obtain, first, adequate interpretation and, second, maximum benefit from the examination. Radiographing has done much to develop and establish confidence in fusion-welded pressure vessels and, while it still remains by far the most reliable method of determining weld soundness, it has certain limitations. Tightly compressed separations in any orientation and cracks which lie in a plane perpendicular to the rays may escape detection. This inspection method is also not sufficiently sensitive for the detection of micro cracks which sometimes occur in weld deposits.

The radiographic technique used is required by the ASME Boiler Code and the API-ASME Code Rules to detect defects equal to or greater than 2% of the plate thickness, as checked by the use of a standard penetrameter with each exposure. The penetrameter consists of a thin metal strip of material similar to the base plate not exceeding 2% of the weld thickness and containing three small holes (of diameter equal to two, three and four times the penetrameter thickness, respectively; $^{1}/_{16}$ in. min. for X-rays and $^{3}/_{32}$ in. min. for gamma rays). The greater the sharpness of the image and the contrast, the greater will be the probability of detecting cracks, which are by far the most

detrimental weld defects. Using good technique and the proper film, it is possible to attain sensitivities with X-ray better than 2%, at least in thicknesses up to 1 inch. Because of this some fabricators use fast film where this will satisfy the code, even though the use of slower film would result in greater sensitivity.

X-ray machines up to two million volts are available, with which it is economically practicable to examine welded joints 6 in. or more in thickness; 200,000- to 400,000-volt machines are most common. It is difficult to compare the merits of X-rays and gamma rays since both have optimum fields of application. Radium has the advantage of being portable and is suitable for extremely heavy thicknesses and locations and shapes which are unsuited to a standard X-ray machine. For general pressure vessel applications, particularly in thicknesses up to $2^1/_2$ in., the X-ray is preferred because of sharper definition, greater contrast, greater speed of examination and reduced cost.

The following briefly outlines ASME Code acceptance standards for completely radiographed welds: (for details see Par. P-102(h)(12) of the ASME Power Boiler Code, Par. U-68(h)(12) of the ASME Unfired Pressure Vessel Code and Par. W-524 (i) of the API-ASME Code).

1. All welds containing cracks or zones of incomplete penetration are not acceptable.
2. Inclusions or cavities are acceptable if not greater in length than $^1/_3T$ (T is the plate thickness) or $^3/_4$ in. and the sum of their longest dimensions does not exceed T in a length of $12T$.
3. Porosity in welds is judged as acceptable or not acceptable by comparison with a standard set of radiographs.

For Par. U-201 vessels subjected to spot radiographing the ASME Boiler Code liberalizes the minimum acceptance standard by allowing twice as much porosity and inclusions up to $^2/_3T$.

Radiographic examination of welds in nozzle attachments on radiographed vessels is not required by code rules unless they are of the inserted butt-welding type since radiographed welds of other types of nozzles cannot be clearly interpreted. Up to the present, no substitute examination has been specified to assure nozzle welds of comparable safety to main seam welds. (See Chapter 42 for further information on inspection methods.)

Magnetic Particle Examination

The magnetic particle method is sometimes specified for nozzle welds which cannot be radiographed and also as a supplementary examination for welds which are radiographed. The State of Ohio requires such supplementary examination of main seams of boiler drums. Minute surface cracks which may not be detected by X-ray can be detected by this method. Subsurface defects also may be located depending on their magnitude, shape and distance below the surface. This type of examination is especially useful for checking the root of a weld after chipping or repair cavities for removal of all defects preparatory to rewelding. It is not applicable to nonmagnetic materials.

For magnetization, direct-current magnetizing current is generally used in pressure vessel applications, being superior to a.c. in detecting subsurface defects. Full wave, rectified a.c. with an initial surge of higher current is used; half-wave rectified current is a later development. The dry powder method is commonly considered superior to the wet method for subsurface flaws.

As in radiographic examination, properly developed technique and skilful interpretation are essential. Controlled sensitivity to suit each application will avoid on the one hand failure to locate flaws and on the other hand false indications (ghost lines). A disadvantage of this method is that abrupt changes in structure, composition or similar effects which influence the magnetic field give the same indications as flaws. For further information see Chapter 42.

Fluorescent Penetrating Oil

The use of fluorescent penetrating oil is a comparatively recent development. It is suitable for detection of surface defects only and may be used on any material. On magnetic materials the use of the magnetic particle method is preferred. The penetrating oil will enter an opening of 4 microns. After application of the oil and removal of excess from the surface, the surface is examined under ultra-violet light. The method is particularly suited to the detection of micro cracks in welds and has also been used in lieu of liner

tightness tests, in the inspection of welds made in attaching corrosion-resistant linings.

Other Methods

Surface inspection of welds is sometimes made by grinding, polishing, acid etching and then examining with a low-power magnifying glass. An alternative method is to wipe the surface with a volatile liquid such as naphtha, and after the surface is evaporated dry, to dust with talc or other hygroscopic powder. This draws the liquid from the flaw as a wet line or area.

New developments such as supersonic and ultrasonic testing, while not in general use, show promise and may find a place in these applications.

Spot Examination by Sectioning

Random examination by the extraction of weld samples which are then sectioned, etched and examined has long been practiced by insurance agencies and is now a recognized code method of spot examination. The sample is generally obtained by trepanning a small plug, but special spherical saws are now available which remove a boat-shaped specimen, and the resulting cavity is more rapidly repaired by welding, with less risk of introducing a defect. Spot radiography is preferred over this method when facilities are available because a greater portion of the seam is examined and it is non-destructive.

Order of Quality Examination

It is common practice to complete radiographic and other quality examinations before a vessel is stress relieved and tested. It might be expected that somewhat greater assurance of soundness would be obtained if the welds were examined subsequent to one or both of these operations. However, there is no evidence that stress relief or hydrostatic testing unduly propagate defects and economic considerations greatly favor the established practice. Examination as a final step entails additional preliminary radiography or additional stress relief and testing operations, with appreciably increased handling charges. If a welded seam is to be subjected to a forming operation examination should be made after forming.

Testing of Completed Vessels

The practice of subjecting a completed vessel to a test which will produce stress somewhat above the design maximum is an established safety measure of long standing. The principal objective aside from the detection of leaks is to give some assurance of the absence of serious defects in workmanship, materials and design. The test does not guarantee that the vessel will withstand subsequent applications of the same pressure or that periodic applications of the lower service pressure might not produce failure. For reasonable assurance of safe construction other inspection for the detection of flaws is essential as outlined under Inspection.

Hydrostatic Testing

Practically all vessels are given their final test by means of hydrostatic internal pressure. The test for riveted vessels has long been standardized at 50% greater than the maximum allowable design pressure. When welded vessels were first sanctioned by the ASME Boiler Code, the test pressure was established at two times the maximum allowable working pressure (equivalent cold pressure in the case of a high-temperature vessel), this higher value being selected to increase the probability of bringing out defects and to better demonstrate the safety of welded construction to prospective users and authorities. The ASME Code still retains this test basis except for boiler drums which are designed to the higher stress level now permitted, which are required to be tested at $1^1/_2$ times the maximum allowable working pressure.* The API-ASME Code requires a test of $1^1/_2$ times the maximum allowable working pressure based on the weakest part of the vessel as fabricated, so that the resultant test pressure is higher when excess metal has been uniformly provided in the design for corrosion allowance or other reasons.

Arguments in favor of high test pressures are the resulting greater stress relief and improvement in circularity. Opposed to this view is the contention that high stress may propagate defects not detected in unradiographed vessels, which might remain dormant under lower stress.

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* A uniform test requirement of $1^1/_2$ times the maximum allowable work pressure is now being considered.

Hammer Testing

Vessels which have not been radiographed and stress relieved are required by both the API-ASME and the ASME Codes to be given a shock test as an additional check for soundness of welds. This is accomplished by striking the plate with a hammer at 6-in. intervals on both sides of all welded joints. The weight of the hammer in pounds should be approximately equal to the thickness of the shell in tenths of an inch, but should not exceed 10 lb., and the plates should be struck with a sharp, swinging blow. The edges of the hammer should be rounded to prevent defacing the plates.

For vessels over 12 ft. in diameter, or over 20 ft. in vertical height, this test is applied when the vessel is not under internal pressure prior to the hydrostatic test. For smaller vessels this test is combined with the hydrostatic test and hammering is done when the pressure reaches a specified value ($1^1/_2$ times the maximum allowable working pressure for ASME U-69 or U-70 vessels and $1^1/_4$ times the maximum allowable working pressure for ASME U-201 and API-ASME vessels).

ASME vessels which cannot safely be filled with water are required to be hammer tested prior to a pneumatic test.

Opinion varies as the value of such testing, which is at least dependent as to effectiveness on the energy with which the blows are struck and the magnitude of the resulting hydraulic hammer.

Pneumatic Testing

Vessels which are not designed for liquid contents sometimes cannot support a hydrostatic test load and are therefore given a pneumatic test. In recognition of the increased hazard involved in subjecting a vessel to over-pressure in this manner, the codes permit testing at a lower pressure. The ASME requires a test of 25% above the design pressure while the API-ASME Code requires 10%.

To obtain a somewhat better test of areas affected by structural supports, such vessels are sometimes given a hydrostatic-pneumatic test in which the liquid load is comparable to the operating load or load which may be sustained, on which the air pressure is superimposed.

In view of the measurably greater energy stored, pneumatic tests are potentially hazardous and should be used only where hydrostatic testing is not practicable. In applying this type of test, all persons should be withdrawn from the vicinity while the pressure is being increased. Pressure should be raised in easy stages with careful inspection at each stage. Practice permits approaching the vessel for inspection while under pressure if the pressure has remained constant for some minutes or, preferably, has been reduced somewhat below the last maximum applied.

Under no circumstances should a vessel under air or gas test pressures be subjected to a hammer test or other form of shock loading.

Proof Testing

Vessels or vessel portions, the strength of which cannot be accurately calculated, must pass suitable proof tests. The ASME Code requires that the proportional limit of the weakest part be determined by hydrostatic test and measurement of deflection. The allowable working pressure is established at a suitable proportion of the test value. The API-ASME Code requires that the vessel sustain a pressure of 1.5 times the desired maximum allowable pressure without showing yielding as evidenced by the flaking off of a brittle coating. It is recognized that such tests are usually capable of detecting only relatively appreciable or wide-spread yielding. Their dependability can be increased by using correctly positioned strain gages of short gage length and deflection gages.

Routine Testing

The ASME Code does not cover testing in service, leaving such matters to users and enforcement authorities. Periodic testing at not less than $1^1/_2$ times the maximum working pressure is the generally accepted practice, particularly if the material suffers deterioration in service due to corrosion or other reasons. The API-ASME Code requires periodic testing as metal added for corrosion allowance disappears in service, except that such tests are not required if the seams were originally radiographed or if they were subjected to the maximum test stress for the full thickness in the initial test.

FIELD-ASSEMBLED VESSELS

It is necessary to field assemble vessels which are too large for shop fabrication or for shipment. Shop fabrication practices are adhered to where possible. However, field fabrication is handicapped by:

Inferior equipment such as forming and heat-treating facilities.

Absence of protection against elements and low temperatures.

Economic necessity of using local workmen; usually less effective than an experienced, standing organization.

Vertical and overhead welding which must be done where vessels are fabricated in place.

Vessels in this category are commonly partially fabricated in the shop and shipped to the field in sections for final assembly. All parts are formed in the shop to the correct shape and dimensions, and are chamfered for welding. Nozzles are generally prepared and cut to correct length, but are not installed unless they are located either in a head or in a section which can be shop fabricated as a unit. It is becoming a more common practice, however, to shop weld all sections which can be shipped.

The lack of good forming facilities in the field makes it very difficult to correct poor fit-up, dimensional errors, etc., hence careful inspection and control of the shop forming and fitting up are of the greatest importance. Wide welds are not a cure for poor fit-up and should be avoided. Complete trial fitting and match marking prior to shipment are sometimes advisable to assure proper field assembly of an unusually complicated vessel or a vessel of a type new to the fabricator, but such operations are unnecessary and wasteful if the structure is simple and of a standard type. Holes for field-installed nozzles are generally cut in the field.

Adverse weather and the problem of obtaining skilled labor at the assembly site are factors requiring the utmost vigilance on the part of the fabricator and inspectors if satisfactory work is to be obtained. Welding on wet surfaces must be avoided. Satisfactory platforms with shelters and wind guards should be provided if personnel are to perform up to their potential skill. Careful storage of welding electrodes is necessary to avoid moisture absorption and resultant detrimental effect on the quality of weld deposits.

Plates for main seams generally are scarfed to single-vee or double-vee grooves and occasionally to U grooves. The latter are used primarily for very thick plates and where the work can be arranged for down-hand position welding essentially duplicating shop conditions. Most fabricators prefer double-vee grooves for the main seams of plates over $^1/_2$-in. thick, which allows balanced welding and greater control of distortion, which is extremely important in field work. For circumferential seams in vertical vessels a single bevel or double bevel groove with 45-deg. bevel angle is sometimes used. The increased use of radiographic inspec tion in the past few years has indicated, however, that less incomplete fusion results where a vee groove of about 60 deg. rather than a single 45 deg. bevel groove is used in the horizontal position.

Preheating is being employed increasingly, not only for welding alloy steel plates but also for welding thick, low-carbon steel plates. During cold weather, all plates should be warmed to at least 60°F. before and during welding. Preheating by means of torches has been extensively used, but it has been found rather difficult to maintain uniform preheat, particularly on vertical seams. Better results have been obtained through the use of resistance strip heaters.

For welding in other than the flat position, successful use has been made of the backstep sequence, a welding technique wherein successive sections of a weld are deposited opposite to the direction of progression. Likewise, the use of backing strips has been found advantageous in promoting complete penetration and protecting welding at the root from the effects of the wind, lessening the possibility of root defects remaining after removal of the backing strip and back-chipping or gouging.

Thorough inspection is even more important than for shop fabricated vessels with emphasis on groove angles, root openings, back-chipping of welds, etc. Visual inspection should be supplemented to some degree by radiographic or magnetic particle inspection, the amount depending on the importance and severity

of the intended service. Complete radiographic examination, little used in the field a few years ago, is becoming increasingly common for petroleum refinery vessels subject to severe temperature or pressure service.

The field testing of large vessels often introduces unusual problems. Where the vessels and supports are adequate for liquid weight, hydrostatic testing can be performed. To permit an adequate test of the upper portion of such vessels, it is sometimes necessary to provide excess thickness in the design of the lower vessel parts. There is need for rules covering a range of acceptable test pressures for vessels tested in the vertical position, so that portions at different elevations are adequately tested but not seriously over-stressed. When a vessel does not operate full of liquid, it is sometimes impractical, for economic or other reasons, to design for liquid load, and in such cases pneumatic or combination pneumatic-hydrostatic loading is employed. The testing of a large vessel by any method involves appreciable hazard in the event of sudden extensive failure. Due to the greater energy stored in a pneumatic test, the shattering effect is proportionally more devastating, and precautions, such as radiographic inspection of main seams, magnetic particle inspection of attachments, and stress relief where possible, all appear advisable. Where stress relief is accomplished by flue-gas circulation, a pneumatic test at temperature can be conducted with reduced pressure, and hence with corresponding reduction in the stored energy.

Stress relief of large vessels in the field presents a difficult problem, but is being successfully accomplished in an increasing number of applications. Generally, the vessel is in its final position and heavily covered either with permanent or temporary insulation, and is heated by internal gas burners, or preferably by circulation from an external flue-gas generator. One very satisfactory arrangement consists of a portable generator producing flue gas at 1200 to 1300°F. with recirculation by means of a blower, and provided with dampers so that flow within the vessel can be reversed at will, giving excellent control of metal temperatures. Similar applications without recirculation or reversal of flow have been successfully employed, but result in greater temperature variation and waste of fuel. If heating is to be done by internal gas burners, special attention must be given to the choice and location of burners and gas flow details to assure reasonably uniform temperature distribution and to minimize the hazards of lighting the burners, and of maintaining combustion when the positions of the dampers are changed.

THIN-WALLED PRESSURE VESSELS

The manufacture of welded thin-walled vessels presents certain problems peculiar to this class of vessel. Vessels up to 1/4-in. plate thickness and about 36-in. maximum diameter might be placed in this category. Because of thickness, size or service limitations, the ASME Boiler Code allows certain details for such vessels which are not permitted for larger vessels. A large number of such vessels are manufactured on a production line basis.

Design details which are common to vessels of this class are inverted heads, single vee welds, lapped seams with double welds and also with single welds, and predominantly threaded openings. For ease of fabrication, many vessels contain excess thickness which is fortunate since corrosion can quickly impair the safety of thin walls. This is recognized in the ASME Unfired Pressure Vessel Code Alternate Rules where corrosion allowance is specified for air or water vessels and vessels in other corrosive service.

Cold pressed heads are commonly used without stress relief, with possibly reduced shock resistance and increased possibility of cracks along welds. Fit-up requires careful attention, particularly on girth seams, and automatic welding must be constantly controlled to assure that the weld straddles the butted plates, which are usually not scarfed. Since small electrodes are necessary, plate surfaces must be free of scale to assure thorough fusion at joints and around openings. Heavy overlays do not compensate proportionately for incomplete fusion and undercutting may seriously reduce the strength of light walls.

For economic reasons, hydrostatic tests are of minimum duration. Special provisions are made for testing mass-production vessels. (See ASME Boiler Code Case No. 1054.)

MULTI-LAYER OR BANDED VESSELS

This type vessel is usually intended for use at extremely high pressures and is generally built to user or manufacturer specifications as no code rules have as yet been adopted.

In one design the shells are made up of a multiplicity of layers of descaled steel plate each about $^1/_4$-in. thick except the innermost layer which is generally about $^1/_2$-in. thick. Each successive layer is wrapped under tension around the preceding assembly and longitudinal seams welded using the underlayer as a backing strip. It is stated that shrinkage in these welds further increases the tightness of layers. Each shell course is completely assembled prior to making the girth welds which extend continuously through the entire thickness, eliminating the layer construction in these areas. Heads are usually solid forgings, and a number of vessels have been fabricated and are in service, some since 1931. Stress relief after fabrication is not advocated as this would relieve initial prestress developed in the layers, and it is contended that longitudinal slippage between layers affords relief against the accumulation of excessive residual welding stresses at girth seams, so that stress relieving is not essential. Radiographic or other quality examination of completed welds is of limited value and is not the usual practice.

In another design, banded construction is used. The inner layer is fabricated to half the required thickness with hemispherical heads using conventional pressure vessel practice, including X-ray examination and stress relief. The cylindrical section is then reinforced against hoop stress by shrinking one or more layers of narrow bands around the inner shell. The circumferential edges of these bands are not welded and longitudinal stress is carried by the inner shell only.

INTERNALLY INSULATED VESSELS

Vessels for certain applications involving high operating temperatures are now being built in which internal insulation is used to reduce the working temperature of the pressure shell. Special attention must be given to details to prevent condensation or vapor flow through or behind the insulation, which would result in loss of insulation by erosion and increased conductivity. The degree of vapor flow through the insulation is a function of the flow velocity in the vessel or other factors which increase the pressure drop such as tower packing and catalyst beds. Such flow may be reduced by metal vapor barriers incorporated into the insulation which, to be effective, must be welded to the shell. The conductivity is increased in proportion to the amount of metal used. Bonding cements and plastic insulations do not always provide continued adherence to the metal wall and, in general, the resistance of the materials used to corrosion and temperature must be examined. Many gases such as hydrogen and hydrocarbons have higher conductivity than air, increasing heat loss which is further increased by the effect of pressure.

Many types of internal insulation have been used such as:

Unreinforced monolithic heat-resisting or insulating concrete.

Insulating block covered by concrete panels or supported refractory walls (similar to boiler walls).

Insulating block or concrete faced with a vapor-tight metal shield sealed to the vessel wall at one end.

Insulating concrete covered by refractory concrete panels reinforced and attached to the vessel wall by clips or studs.

Insulating brick or insulating and refractory brick.

CORROSION-RESISTANT LINERS AND CLAD PLATE

Methods Used

Corrosion protection for pressure vessels may be secured by:

Excess shell thickness.

Painting, sprayed metal coatings or wash coatings.

Refractory, concrete, rubber, lead, glass or plastic linings.

Sheet metal linings.

Clad and integrally bonded shell plates.

Of most interest in so far as welding is concerned is the use of liners or clad plate.

Liners Attached by Welding

Sheet metal liners are commonly attached by

Spot welding.
Plug or slot welds.
Arc welding between linear edges and against shell (strip lining).

Any weldable material with suitable corrosion resistance may be used, $^{5}/_{64}$ and $^{7}/_{64}$ in. being the most commonly employed thicknesses.

Strip lining is the accepted designation for construction involving liner strips 3 to 6 in. wide and 3 to 5 ft. in length, with the long dimension generally circumferential. Attempts to attach the edges of two adjacent strips to the vessel by one weld pass have not been satisfactory. Instead, the edges of one strip are first welded, then the adjacent strip layed up and tacked in place. If this next strip is brought up to the edge of the previous fillet weld, the attachment can be completed by a second pass. However, many fabricators find it preferable to separate the strips sufficiently to permit fillet welding this strip to the base plate and then completing the attachment by a third pass filling the gap between the fillet welds.

See Chapter 37B for methods of applying liners by welding.

The degree of tightness required of an attached lining also depends on the intended service. For most petroleum applications small leaks are not of great consequence except in occasional bulging of the liner due to coking behind it. In many chemical plants or other services, however, the base metal might be corroded at an accelerated rate by such leakage. Liners are tested by various methods such as:

Introducing air or other suitable medium at an appropriate pressure between the liner and the shell and checking attachment welds with soap suds or other suitable fluid. The test pressure should not exceed about 75% of the pressure which would cause bulging of the liner.

Testing the vessel hydrostatically with petroleum followed by steaming out, then inspecting the liner surface for traces of oil which will often seep out from cracks and porous areas.

Introducing water at high pressure between spot-welded liners and the base plates.

Inspecting the welds by the fluorescent penetrating oil method or, in the case of magnetic materials by the magnetic particle method.

Testing the vessel hydrostatically, followed by heating in a furnace to 400° F. Moisture behind the lining in evaporating often leaves a trace of scale to mark a defective location.

Flexing of the liner sheets in service due to repeated applications of the service pressure occasionally results in leakage. This is more apt to occur where the liner or base material is subject to unusual air hardening, temper brittleness or age hardening.

Arc-welded liners are usually attached with $^{1}/_{8}$-in. or $^{5}/_{32}$-in. diameter electrodes using low amperage and a short arc to minimize dilution by base metal. The base metal should be thoroughly cleaned prior to welding and all weld passes carefully cleaned. Sheet liners are now also being attached by submerged arc welding. Since the attachment of a lining involves extensive welding on the base metal with possible propagation of defects, it is important in the interests of safety that the procedure be thoroughly investigated for soundness and ductility of deposits. The ASME Boiler Code Committee has established suitable requirements in Case No. 1078.

Clad Plate

Steel plate with the corrosion-resistant lining continuously bonded thereto is produced by several processes and finds wide application in pressure vessels. A detailed description of the process will be found in Chapter 37A. Such material is particularly suited to severe service where a high degree of attachment is desirable and where leakage through the corrosion-resistant lining could not be tolerated.

The ASME Boiler Code Committee has given careful attention to the use of clad steels and to the relative stress in the cladding and base material, and in Case 896 has approved the use of certain chromium, chromium-nickel (austenitic), nickel, and nickel alloy clad steels, with the design based upon full thickness of the composite material under some conditions of service. For other conditions, the base metal thickness only must be used in calculations. The nominal cladding thickness is generally 10 or 20% of the composite thickness but other pro-

portions may be obtained. No difficulties have been reported as a result of differential expansion between cladding and base plate in operation with service temperatures to 1000°F. and higher.

In welding clad steels, it is of great importance that the procedure used recognize the degree of possible variation in cladding thickness and be such as to avoid depositing weld metal of base metal analysis on the corrosion-resistant cladding or weld metal or so close thereto as to cause contamination. The low-alloy deposit resulting is likely to be very air hardening and susceptible to thermal shock cracking. If, prior to welding the base metal the cladding is removed from the edge of the welding groove $^1/_8$ to $^3/_{16}$ in. and the plate edge checked by etching with 20% nitric acid, trouble from this source can be eliminated. The base metal weld is completed first, after which the corrosion resistant weld is made.

BIBLIOGRAPHY

1. *The Design of Ellipsoidal Heads for Pressure Vessels,* T. W. Greene, ASME Transactions, 1929.

2. *Stresses in Dished Heads of Pressure Vessels,* C. O. Rhys, ASME Transactions, 1931.

3. *Effect of Openings in Pressure Vessels,* J. H. Taylor and E. O. Waters, Mechanical Engineering, May 1932.

4. *Openings in Cylindrical Drums,* D. S. Jacobus, Mechanical Engineering, May 1932.

5. *Strength of Thin Cylindrical Shells Under External Pressure,* D. F. Windenburg and H. E. Saunders, ASME Transactions, November 1934.

6. *Collapse by Instability of Thin Cylindrical Shells Under External Pressure,* D. F. Windenburg and C. Trilling, ASME Transactions, November 1934.

7. *Formulas for Stresses in Bolted Flanged Connections,* E. O. Waters, D. B. Wesstrom, F. S. G. Williams and D. B. Rossheim, ASME Transactions, April 1937.

8. *Fabrication Costs of Boilers, Tanks and Pressure Vessels,* W. G. Theisinger, Mechanical Engineering, April 1945.

9. *Manual for the Design of Ferrous and Nonferrous Pressure Vessels and Tanks,* Karl Siemon, Edwards Bros., Third Edition, 1946.

10. *Simplified Methods for Calculating Stresses in Pressure Vessels,* Carsten F. Boe, Chemical and Metallurgical Engineering, March 1946.

11. *Welding Multilayer Steel Pressure Vessels,* Materials and Methods, June 1946.

12. *Steel Plates and Their Fabrication,* Lukens Steel Co., 1947.

13. *Pressure Vessels for Industry,* Harry N. Spring, Jr., McGraw-Hill Book Co., 1947.

14. *Biaxial Stresses in Rigid Vessel Simulated in Notched Tension,* G. Brewer, Metal Progress, January 1947.

15. *Master Charts for the Design of Vessels Under External Pressure,* D. F. Windenburg, ASME Transactions, May 1947

16. *Unfired Cylindrical Vessels Subjected to External Pressure,* F. V. Hartman, ASME Transactions, May 1947.

17. *Computing Strength of Vessels Subjected to External Pressure,* R. G. Sturm and H. L. O'Brien, ASME Transactions, May 1947.

18. *Advanced Techniques for Pressure Vessels,* Gerald E. Stedman, Welding Engineer, December 1947.

19. *Fabrication of Clad Steels,* L. W. Williams, Lukens Steel Co., 1948.

CHAPTER 52

SHIPS*

INTRODUCTION

A SHIP IS A FLOATING structure and the problems involved in its design are somewhat different from those which confront the designers of land structures such as bridges and buildings. If the ship is to remain afloat and be fit for carriage of dry and perishable cargo, water must be kept out of the hull, so tightness is an essential consideration. The utmost economy in weight of material is also of outstanding importance as any excess of material provided in the design over and above the minimum required for structural strength, including a suitable margin for corrosion and wear, has to be carried around with the ship, with a resultant sacrifice in deadweight carrying capacity, speed and other factors.

Ships differ widely in type and conditions of service and range from the small towed barge of simple box section engaged in smooth water service to a large liner operated in trans-oceanic trades. In a barge the hull stresses are comparatively simple and readily calculable. Ocean-going vessels propelled through the water in all conditions of wind and weather are subject to hogging and sagging stresses in waves, as well as to stresses caused by rolling, pitching and slamming. The problem of economic structural design of such vessels is complex and their scantlings have been evolved largely on the basis of experience with due regard to scientific methods of analysis and evaluation.

It was only through the extensive use of welding that the tremendous war production shipbuilding program in U.S. shipyards could have been accomplished in the limited time available. For some years prior to the war emergency there had been a gradual trend toward welded construction in order to effect savings in hull weight and with a view of overcoming some of the service troubles encountered in riveted ships. Under stress of weather or as a result of bumping, etc., rivets are likely to slacken and caulked seams to spring. An accumulation of even minor leaks from such causes can easily result in serious damage to perishable cargoes in freighters or in oil contamination in the case of tankers.

By the use of welding, hull weights are reduced from 5 to 15% depending upon the extent of welding and the type of ship. Increased efficiency can be brought about through this saving in weight of the steel structure and by the use of high temperature, high pressure steam propelling machinery which is facilitated by the fact that the piping and boiler drums and a great many other machinery parts in these modern installations are invariably of welded construction.

In addition to savings in the original cost of construction, economy in fuel operation and increase in deadweight carrying capacity, there is a further saving in hull maintenance costs which in some instances is claimed to have amounted to around 25%.

GOVERNING RULES AND REGULATION

Merchant vessels, War Department vessels and many merchant-type Naval vessels are constructed in accordance with the requirements established by the U.S. Coast Guard and by the American Bureau of Shipping. Naval combatant

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* Prepared by a committee consisting of David Arnott, American Bureau of Shipping, *Chairman;* David Bannerman, Jr., American Bureau of Shipping; A. G. Bissell, Bureau of Ships; Paul Ffield, Bethlehem Steel Co.; LaMotte Grover, Air Reduction Sales Co.; T. M. Jackson, Sun Shipbuilding & Drydock Co.; E. M. MacCutcheon, David Taylor Model Basin; T. B. Smith, Bethlehem Steel Co.

vessels and certain other special types are constructed in accordance with U.S. Navy specifications.

The American Bureau of Shipping requirements can be found in its *Rules for the Building and Classing of Steel Vessels,* which is revised periodically.

Coast Guard regulations are a part of the *Code of Federal Regulations* and come under Title 46, Shipping; Chapter I, Coast Guard: Inspection and Navigation. The following sections apply to welding:

Subchapter D—Tank Vessels—Part 31.3-2, 37.2.
Subchapter F — Marine-Engineering Regulations, Part 56.20.
Subchapter G—Ocean and Coastwise, Parts 59.15 and 59.30.
Subchapter H—Great Lakes, Parts 76.15, 76.15a, 76.18, 76.34.
Subchapter I—Bays, Sounds and Lakes, Parts 94.14, 94.14a, 94.17, 94.34.
Subchapter J—Rivers, Part 113.23
Subchapter M—Passenger Vessels, Part 144.3.
Equipment Lists for Merchant Vessels (Includes list of approved electrodes)

U. S. Navy regulations and requirements covering welding are embodied in Chapter 92 *Welding and Allied Processes,* of the Bureau of Ships Manual and include the following specifications:

General Specifications for Building Vessels of the U.S. Navy, Appendix 5, Specifications for Welding.
General Specifications for Machinery, Section S1-4, Welding and Brazing.
General Specifications for Inspection of Material, Appendix VII, Welding.

Typical examples of data from these specifications are reproduced in suitable parts of this chapter. In addition to the requirements and restrictions indicated above, Chapter 92 includes much general information on welding and welding equipment for use by the Naval service.

MATERIAL

Base Material

Until recently no special grade or quality of structural steel was specified for welded ship construction. However, the use of Bessemer steel was not permitted and the specifications either directly or indirectly controlled the carbon content so as to keep the hardness to a minimum in the heat-affected zone adjacent to the weld. This was formerly accomplished in American Bureau of Shipping and other classification society specifications by placing an upper limit on the tensile strength and leaving the chemical requirements open. These specifications were sufficient to insure a medium carbon steel having the conventional mechanical properties characteristic of the grades of steel which experience has shown to be satisfactory for riveted structures. The U.S. Navy accomplishes the same ends by specifying chemical limits which include a maximum of 0.31% carbon and a maximum of 0.75% manganese and the usual limitations on sulfur and phosphorus.

Within the last few years research has shown the need for a commercial steel which would combine conventional mechanical properties with a higher degree of notch toughness as well as the desirable property of low hardenability in the heat-affected zone. Notch toughness cannot be judged by the conventional mechanical tests of structural steel and special tests are required to appraise it. However, the degree of notch toughness can be approximately regulated by specifying certain limitations on chemistry and steelmaking practice.

Another factor affecting notch toughness is the thickness of the material. If both thick and thin plates are rolled from the same heat of steel, the steel in the thin plates usually will be more notch-tough than the steel in the thick plates. This is due to different degrees of hot reduction, finishing temperatures, cooling rates, etc. In addition, due to the size effect (a geometric factor) notch toughness usually decreases as the thickness increases. Consequently to preserve notch toughness in thick plates they must be made from a more notch-tough steel than that which would normally be suitable for thin plates.

The latest American Bureau of Shipping specifications for hull steel published in 1948 recognize variations in notch toughness due to thickness of plates by specifying three classes. The mechanical properties of all three classes are as follows: tensile strength 59,000–70,000 psi.; minimum yield strength 32,000 psi.; minimum elongation in 8 in., 1,500,000/TS

or 22% in 2 inches. Open-hearth or electric furnace is specified for all three classes.

Class A includes plates up to and including $^1/_2$-in. thick and all shapes. The tensile strength limits insure a medium carbon steel.

Class B covers over $^1/_2$-in. and up to 1-in. thick inclusive. The chemical limits for this grade insure a low carbon (0.23% maximum) high manganese (0.60–0.90%) semi-killed steel.

Class C applies to all plates over 1-in. thick and requires a similar low carbon (0.25% maximum), high manganese (0.60–0.90%), silicon (0.15–0.30%) steel made to a fine grain, fully killed practice.

Filler Metal

Electrodes conforming to the specifications cited in the previous section in this chapter on Governing Rules and Regulations are qualified for naval use by tests in a Naval laboratory, and lists of qualified electrodes are sent at intervals by the Bureau of Ships to Supervisors of Shipbuilding, Naval Inspectors of Ordnance, Inspectors of Naval Material, Industrial Managers, and other offices of the Navy for reference.

Electrodes for welding on vessels classed by the American Bureau of Shipping or inspected by the U.S. Coast Guard are qualified by demonstration by the manufacturer, in the presence of a Surveyor of the American Bureau of Shipping, that the electrodes meet the requirements of the AWS-ASTM *Tentative Specifications for Mild Steel Arc Welding Electrodes.* (See Chapter 38.) The U.S. Coast Guard accepts electrodes approved by the Navy without further testing. Electrodes of the E60 series of classifications are used for all hull construction except that those of the E6012 and E6013 classifications, because of their slightly lower ductility, are not approved for any joints of the shell plating, strength decks, tank top, bulkheads and longitudinal members of large vessels or of galvanized material.

DESIGN

General

In the construction of welded ships, consideration should be given to the yard practices and procedures from the preliminary design stage onward. The structure should be designed specially for welding; a welded structure should never be designed to traditional riveting standards and details. The ideal arrangement is one in which every step of the work is planned in advance from mold loft to final inspection in chronological order, all with a view to making the best and most efficient use of the welding processes.

Hull structures are divided into subassemblies, which are usually fabricated clear of the shipways, preferably in a covered shop. These subassemblies are as large as can be handled expeditiously and be placed aboard ship without holding up other work in the vicinity. Welding in the shop has many obvious advantages over welding aboard ship. The work and equipment are protected from the weather, necessary cleaning is more easily accomplished and the operators are less subject to discomforts which may interfere with the quality of their work. Shorter leads from machines to electrodes, and easy access to machines for correct setting reduce the variables inherent in ship welding. By the use of positioning equipment, or by turning whole subassemblies, the great bulk of welding may be done in the flat position, usually resulting in better quality as well as greater speed. If several identical units are to be made, it is often useful to prepare jigs or forms on which the subassemblies are set up. An important consideration is that supervision indoors is easier and more efficient than supervision outdoors. The designer, therefore, should dispose the material in such a way as to make it easily divided into convenient subassemblies.

Joints in plating and details of welded joints should be so arranged as to permit the application of a suitable welding procedure and sequence without difficulty. It is generally good practice to arrange butts of adjacent strakes of plating in line so as to eliminate the T-shaped intersections of butts and seams which occur when butts are staggered. (See discussion on Distortion and Cracking.)

Subassemblies should be planned so that the welds joining them which must be made on the shipways, will be in the most accessible positions, arranged for flat or machine welding wherever practicable. The root side of such welds should also be accessible for back-chip-

ping and welding, because ship welding practice generally requires joints to be welded from both sides, except where butts are welded to backing strips or to other structural members. In many cases it is possible to join subassemblies by means of lap joints so that no final trimming is required. However, this practice is not usually followed in the shell and strength decks. (See Chapter 39 for more detailed design data.)

Framing

Framing in ship structures includes shell frames, deck beams and bulkhead stiffeners. They are usually of the lightest and smallest section that will provide the required strength, because both weight and space are at more of a premium than in most land structures. They may consist of flat bars in the smaller sizes and of inverted angles, tee bars, bulb angles or channels with one flange removed for larger sizes. In very heavy sections, rolled I-beams or built-up sections may be used. In some applications, serrated sections cut from channels are substituted for angles. Faying flanges should be avoided as they interfere with welding the joints of the plating, they must be set to bevels to suit the lines of the ship and complicate securing watertightness.

Framing members are usually intermittently welded to the plating, except at the ends and at intersections with supporting members. This saves welding footage but not necessarily total deposited metal because the required size of intermittent weld is greater than the required size of continuous weld. Distortion is less and removals for repair are easier than if continuous welds are used. A further advantage is that a fracture in the plate rarely propagates into an intermittently welded frame whereas it almost invariably does propagate into a continuously welded frame.

Framing members such as girders, web frames, stringers or shelves and deep web stiffeners on bulkheads intended to support the other framing, are built up of a web plate and face plate, or made of flanged plates. Rider plates are sometimes added rather than using single heavy face plates. These deep framing members are usually slotted to permit the smaller members which they support to pass through and the smaller members are usually welded to them at the intersections. Slots should in all cases be cut with rounded corners, or a drilled hole should be located where the heel of the member passes through, (see Fig. 1) otherwise cracks may develop in the web of the girder. These deep framing members are also intermittently welded to the plating but with increments spaced closer together than for shallow members.

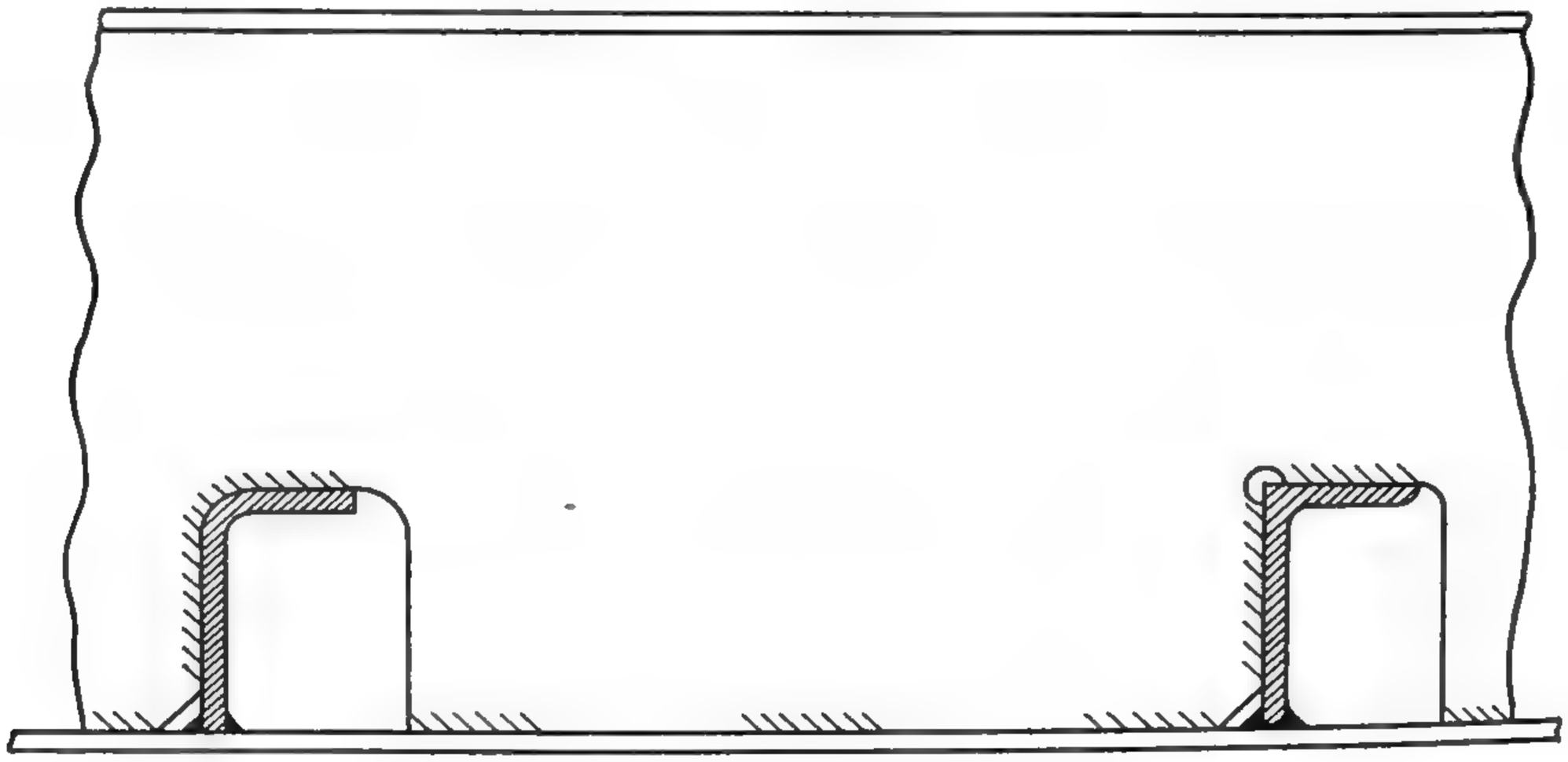


Fig. 1.—Typical Details for Slotting Deep-Framing Members

For access in welding as shown in Fig. 2, framing members are usually scalloped or cut out in way of joints in the plating to which they are attached. In order to maintain the sectional area

of the frames as nearly as possible, the scallops are kept to the smallest practicable size.

To preclude serious defects in butt joints, special care should be exercised in the preparation of angles, tees, bulb

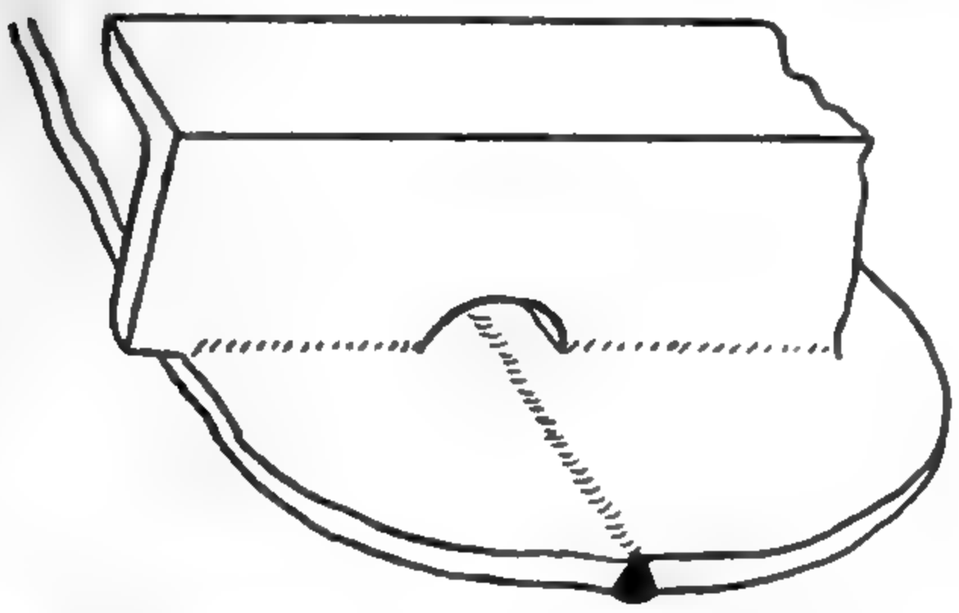


Fig. 2.—Scalloping of Frame at Joint in Plating

angles, etc., for welding, even where these members are of minor structural importance. Figure 3a shows defective welding in a bulwark cap rail; Fig. 3b shows defective welding in a bilge keel.

Standard practice for the arrangement and spacing of fillet welds connecting framing members to plating in merchant ships is included in Table 1. Corresponding information for naval ships is shown in Figs. 4 and 5.

Design Details

In welded ship construction, experience has shown that the details of design are as important to the integrity of the structure as the scantlings of the various members. The effects of notches on the energy absorbed in the fracture of various types of specimens is discussed in Chapter 40.

The guiding principle in the design of details is to avoid abrupt discontinuities and to insure as even stress flow as possible. Good practice has always required tying the ends of major strength members gradually into the adjacent structure, as in the case of long superstructures, or changing deck levels. In welded ships, this must be applied to the smaller details as well.

All openings in any part of the ship should be made with rounded corners. Even small cuts for ventilators, sea chests, etc., should have round corners, which may be made by drilling holes at the corners of the opening, from which the cutting is started. At highly stressed points, such as the corners of cargo hatchways, a radius of one foot or more is advisable, with the curved plate edge ground to a smooth surface or fitted with a face plate. Extensive research with full size specimens of hatch corner details illustrates this point strikingly. (See Reference 10 in Bibliography.) The ends of superstructures should be treated similarly by using long, sweeping fashion plates, ground to a fair curve with the sheer strake edge.

Welds in plating should be located at least a short distance away from a geometric change, since even a slight weld defect has the effect of further concentrating stresses at such a location. (See Fig. 6.) If the toes of the fillet welds attaching two adjacent members to the surface of a plate are so close together as to form a vee between them, the plate may crack between the welds when under stress. Service records show that care must also be taken to avoid even minor discontinuities and to locate welds away from changes of section even in structurally unimportant parts. Instances have occurred where a crack started in some part, such as a bulwark, and spread

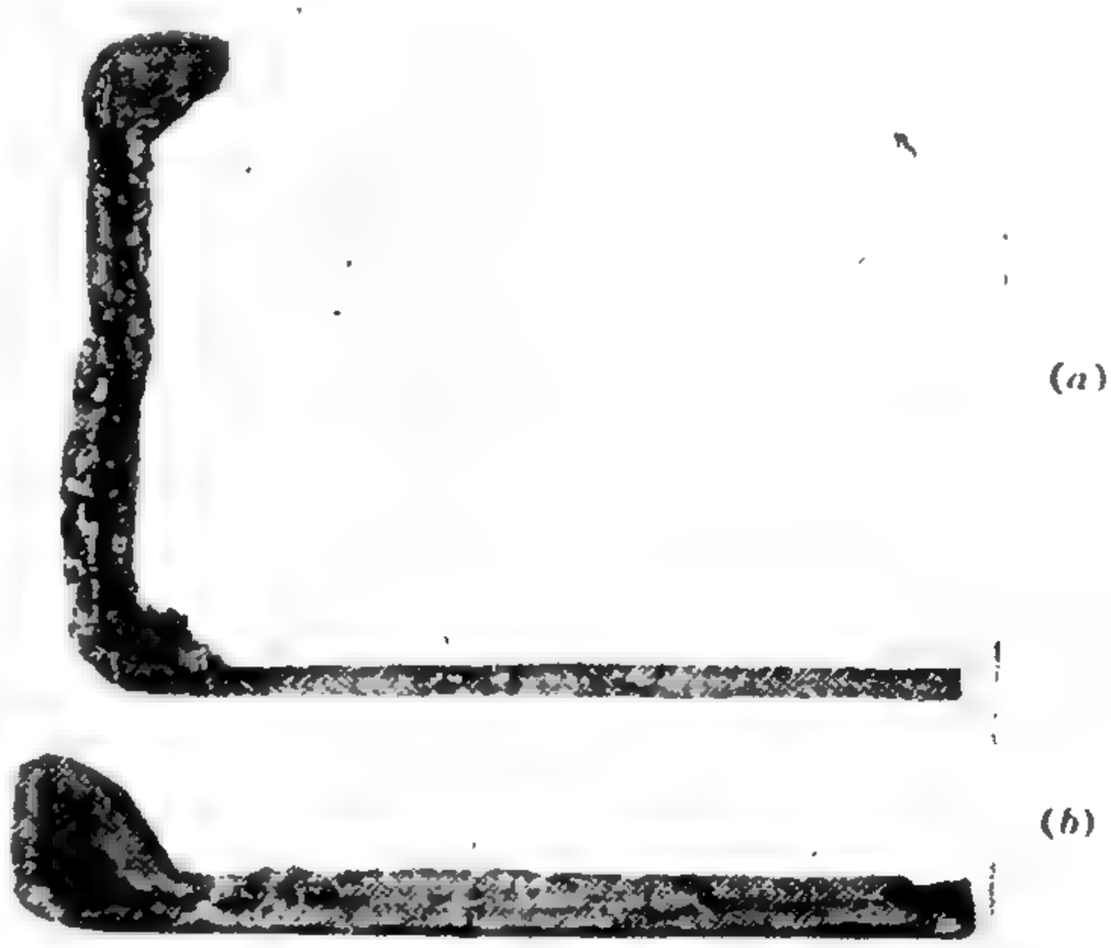


Fig. 3.—Defective Welds

(*a*) Bulwark cap rail
(*b*) Bilge keel

rapidly into the main hull structure from the top of the sheer strake to which the bulwark plate was welded. Many other examples could be cited, but all are basically the same in that abrupt changes or

notch effects, whether the result of design or workmanship, are potential sources of trouble.

Joint Design

The following extract from the Rules of the American Bureau of Shipping cover the details of joints most commonly used in ship construction.

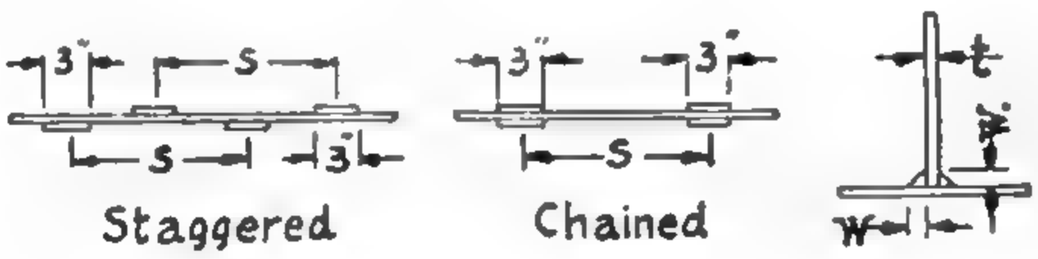
"In general, all groove welded joints are to be welded from both sides. Butt joints of plating not exceeding 1/4 in. in thickness may ordinarily be manually welded without beveling the plate edges; otherwise the edges of both plates are to be similarly beveled from one side or both sides to form an included angle of 60 deg.; the root face or shoulder should not exceed 1/8 in. in depth, and the root opening or gap between plates should be not less than 1/16 in, nor more than 3/16 inch. In all cases the root of the weld is to be backchipped or flame gouged to good sound metal before applying the closing bead.

"When an approved automatic machine process is used to weld both sides of a butt joint, the plate edges need not be beveled, for thicknesses not exceeding 5/8 inch. If manual welding is used to make the backing pass for automatic welding the joint is to be beveled for the manual weld to a minimum of 60 degrees. If details other than the foregoing are proposed to be used, such details are to be submitted specially for approval."

Combination of Riveting and Welding

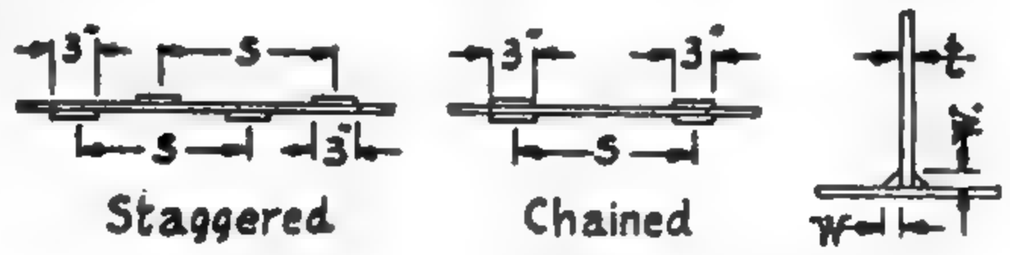
Until greater insurance against major fractures through improved materials or better control of notches is obtained, it is probable that at least certain joints will be riveted, notably in large vessels. Such joints will generally be the connection of the main strength decks to the side shell, longitudinal seams at the bilge, and

Table 1—Spacing of Intermittent Welds

ITEMS		All fillets 3 Inches long				
		Plate thickness "t"				
		Not over .32 Inches	Above .32 to .42 incl. Inches	Above .42 to .52 incl. Inches	Above .52 to .62 incl. Inches	Above .62 to .72 incl. Inches
	Nominal size of fillet "w"	1/4	5/16	3/8	7/16	1/2
† Beams	To decks when on alternate frames and in tanks	11	11	11½	12	12
	To decks when on every frame outside tanks	12	12	12	*12	*12
† Bulkhead stiffeners	Deep tank bulkhead. See Note A	10	10	10½	11	11
	Ordinary watertight bulkhead See Note A	12	12	12	*12	*12
	Non-watertight bulkhead See Note A	*12	*12	*12	*12	*12
Center girders See Note B	To inner bottom or rider plate in way of engines and to shell or bar keel	5	5	5½	5½	5½
	To inner bottom or rider plate clear of engines	6	6	6	7	7
† Frames and floors See Note C	To shell on flat of bottom forward and in aft peaks of vessels having high power and fine form	5	5	5½	5½	5½
	To shell for .15L forward to above load water line and in deep tanks and peaks	10	10	10½	11	11
	To shell elsewhere where spacing exceeds 30". See Note A	11	11	11½	12	12
	To shell elsewhere where spacing 30" or less. See Note A	12	12	12	*12	*12
Floors, single bottom	To center keelson plate in machinery space, wide spaced floors with longitudinal frames and within ½ length in vessels 230 ft. long and above			Double continuous		
	To center keelson plate elsewhere	7	7	7½	7½	8

*Nominal size of fillet "w" may be reduced 1/16 inch in association with spacing given.
†In vessels classed for River, Harbor or Canal Service exclusively the welding of beams, bulkhead stiffeners, frames and floors to the plating may consist of 2½" fillets spaced 12" centers in dry spaces and 3" fillets spaced 12" centers in tanks.

Table 1(Concluded)—Spacing of Intermittent Welds

ITEMS		All fillets 3 inches long				
		Plate thickness "t"				
		Not over .32 Inches	Above .32 to .42 incl. Inches	Above .42 to .52 incl. Inches	Above .52 to .62 incl. Inches	Above .62 to .72 incl. Inches
	Nominal size of fillet "w"	¼	5/16	3/8	7/16	½
Floors, double bottom	Solid floors to center vertical keel plate in engine room, under boiler bearers, on wide spaced floors with longitudinal frames, and in vessels where length exceeds 500 feet	4½	5	5	5	5
	Solid floors to center vertical keel plate elsewhere, and open floor brackets to center vertical keel	9	9½	9½	10	10
	Solid floors and open floor brackets to margin plate	7	7	7½	7½	8
	To inner bottom in engine room. See Note C	5	5	5½	5½	5½
	To inner bottom at forward end. See Note C	11	11	11½	12	12
	To inner bottom elsewhere	12	12	12	*12	*12
Foundations	Main engine girders to top plates, shell, or inner bottom			Double continuous		
	Boiler and auxiliary foundation girders to top plate	4½	5	5	5	5
	Boiler and auxiliary foundation plates to shell, inner bottom, and all brackets, etc.	5	5	5½	5½	5½
Solid webs under 27" deep	To shell and to bulkheads in tanks	9	9½	9½	10	10
	To bulkheads elsewhere	12	12	12	*12	*12
Solid webs 27" deep and over, slotted webs, stringers or girders under 27" deep	To shell and to bulkheads or decks in tanks	6	6	6	7	7
	To bulkheads or decks elsewhere	9	9½	9½	10	10
Slotted webs, stringers or girders 27" deep and over	To shell and to bulkheads or decks in tanks	4	4	4½	4½	4½
	To bulkheads or decks elsewhere	7	7	7½	7½	8
All Face Plates	To webs where area is 10 square inches or less	12	12	12	*12	*12
	To webs where area exceeds 10 square inches	7	7	7	8	8
Intercostals	To shell on flat of bottom forward, and to inner bottom in way of engines	5	5	5½	5½	5½
	To shell and inner bottom elsewhere	10	10	10½	11	11
	To floors	10	10	10½	11	11

* Nominal size of fillet "w" may be reduced ⅛ inch in association with spacing given.

NOTE A—Unbracketed shell and bulkhead stiffeners are to have double continuous welds for one-tenth of their length at each end.

NOTE B—Where center girders are water or oil-tight a continuous weld is to be used on one side of the top and bottom connections with intermittent welds on opposite side spaced 12 inches.

NOTE C—Tank end floors are to be welded to shell, center girder and inner bottom as required for deep tank bulkheads.

NOTE D—Where beams, stiffeners, frames, etc., pass through slotted girders, shelves or stringers, there is to be a pair of matched intermittent welds on each side of each such intersection and the beams, stiffeners, and frames are to be efficiently attached to the girders, shelves, and stringers.

bilge keel shell connections with possibly some additional fore and aft seams in side and bottom shell, and strength decks.

Wholly aside from considerations of crack-arresting or intent to avoid the monolithic character of the all-welded hull, many ship builders find advantage in the combination of riveting and welding in the hull structure. As a rule, this combination takes the form of riveted longitudinal seams in the shell plating in conjunction with welded transverse butts and framing connections. In other cases the framing has been riveted to the shell and riveted butts or seams used only in connecting large assemblies, which in themselves are all-welded.

Among the reasons or advantages for these combinations are:

1. Utilization of equipment and skills still available at standard yards.
2. Faster erection without the necessity of special clips, unnecessary erection holes or holding devices.
3. Greater economy in certain applications, where field welding is costly or difficult.

Welds and rivets should never be combined in the same joint as it is not known how the load would be distributed between them. However, members such as brackets may be welded along one edge and riveted along the other without difficulty.

The combination introduces certain difficulties which sometimes outweigh its advantages. One of the most serious is

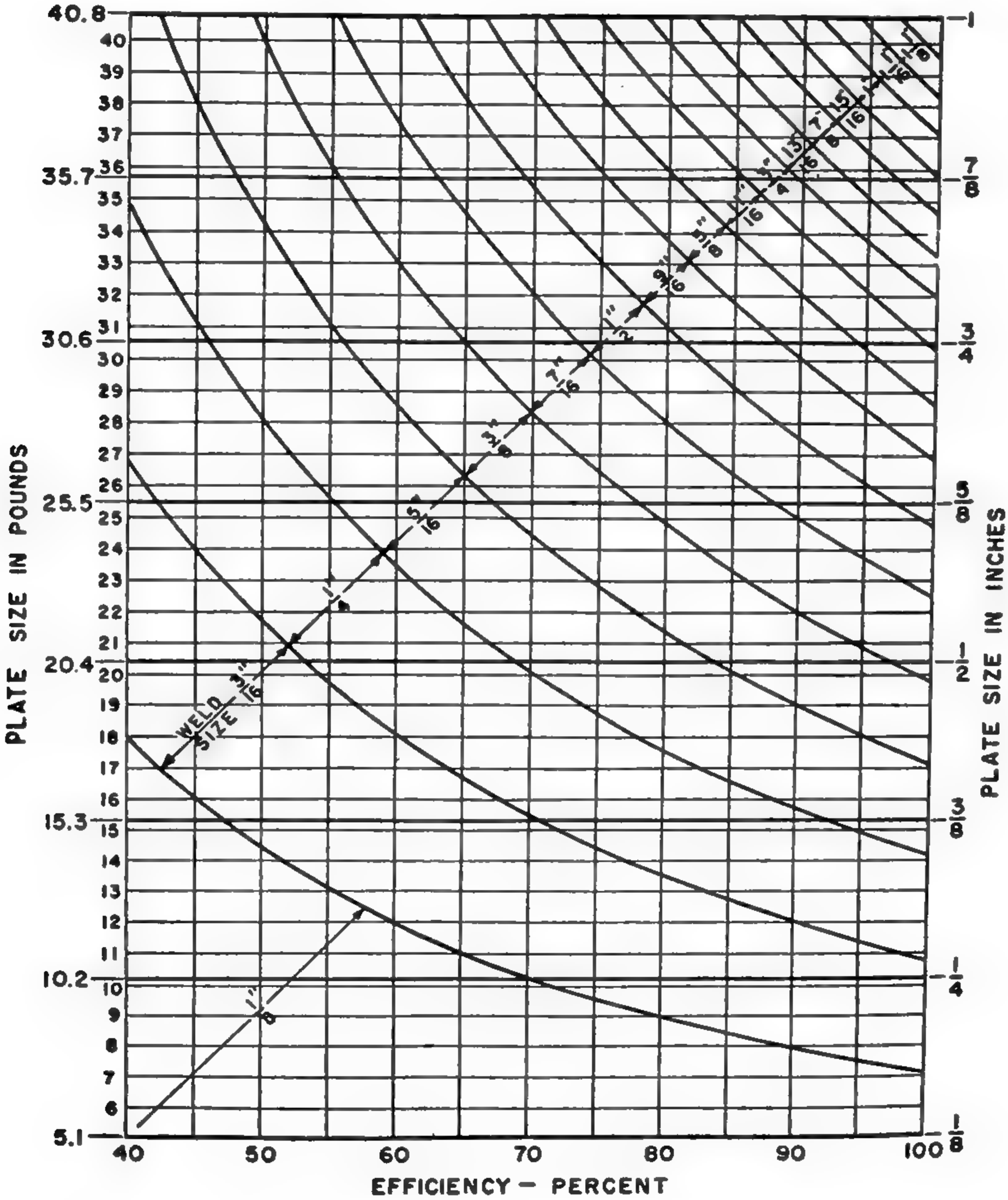


Fig. 4.—Efficiencies of Welded Tee Joints

1. This figure for use only with double fillet-welded Tee-joint welds for medium steel welded to medium or high-tensile steels with electrodes as set forth in the specifications.
2. The plate size to be used in entering this figure is that of the thinner member being joined except that where one member of the joint is made of high-tensile steel, the plate size shall be that of the medium steel member if it has the lesser total strength. Otherwise the size of the fillet weld shall be as set forth in the specifications for high-tensile steel.
3. The weld sizes set forth in this figure have been calculated from the strength of fillet welds weld shall be as set forth in the specifications for high-tensile steel.
3. The weld sizes set forth in this figure have been calculated from the strength of fillet welds shown in Fig. 5 and the minimum tensile strength of medium steel (60,000) psi.

shrinkage due to welding attaching structures, which causes cumulative loss of dimension and requires in practice that the rivet holes be shop-punched (or drilled) in one plate only with the adjoining plate left blank or sub-punched for drilling to size in place on the ship after welding, a procedure which is somewhat expensive. Since the erection holes provided likewise go out of alignment and may require oversizing, they are kept to a minimum. In the subsequent drilling

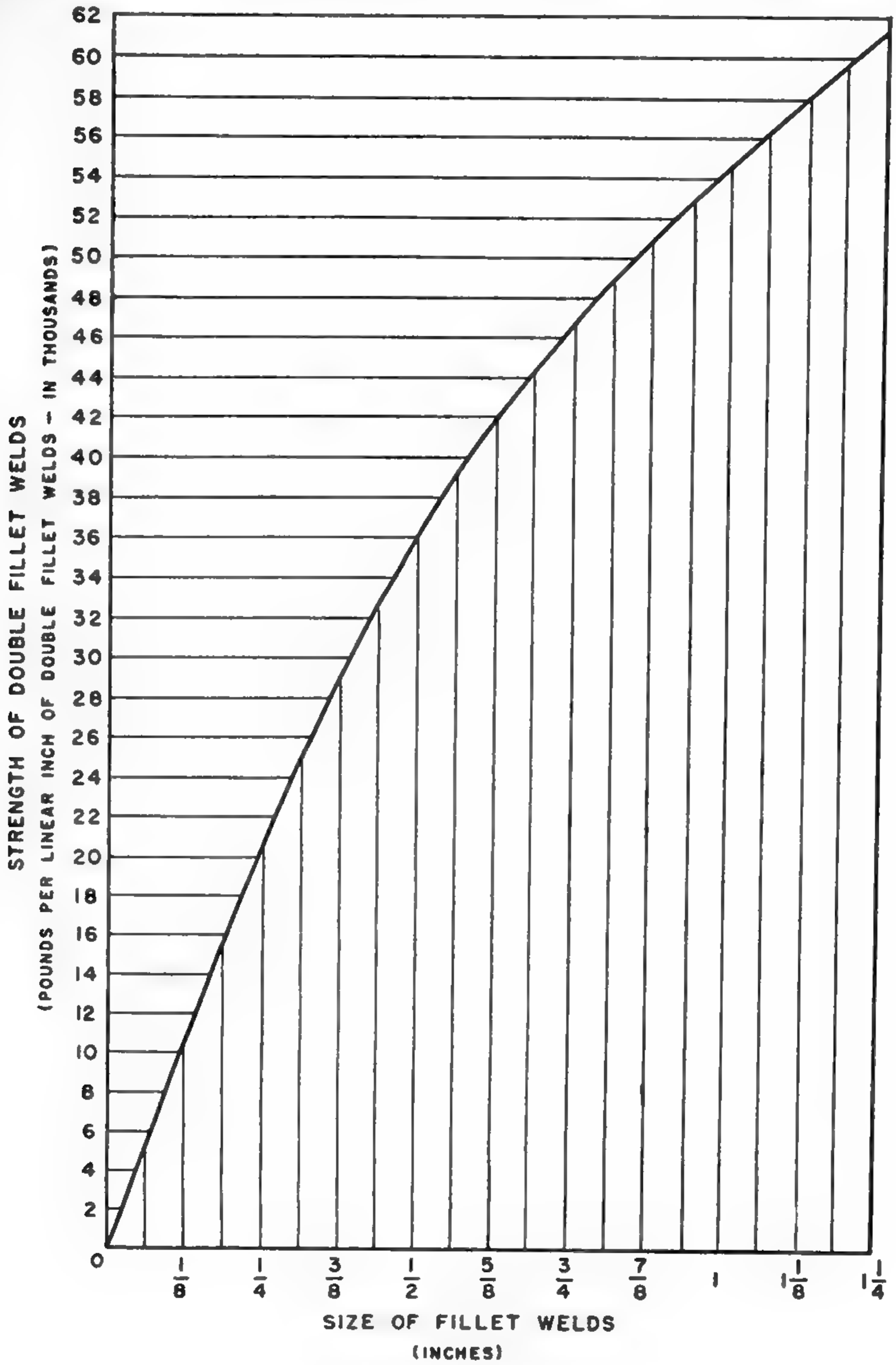


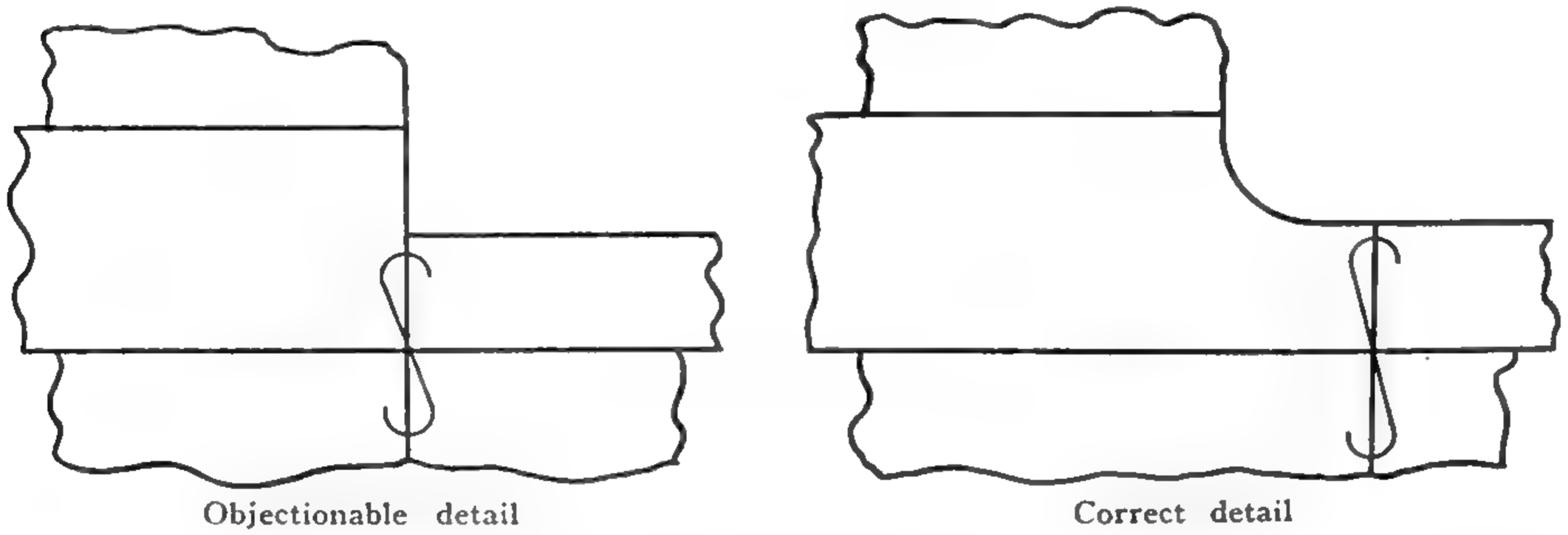
Fig. 5.—Strengths of Fillet Welds

1. This figure for use with all fillet-welded Tee-joint welds (whether continuous or intermittent) for medium and high-tensile steels welded to medium or high-tensile steels with electrodes as set forth in the specifications.
2. The strength of fillet welds set forth in this figure shall be used as the ultimate design strength regardless of the direction of loading.

there is some likelihood of chips and burrs between faying surfaces, which must be removed.

On the other hand, if welding is done after riveting, rivets immediately adjacent to a weld may be loosened by heat or *shouldered* by plate shrinkage.

Extensive tests have been made to determine the extent to which the welding of framing and other attachments influences the rivets in adjacent completed joints and the degree to which this practice may affect residual stress. As a result, approval has been given in many cases to rivet longitudinal seams or butts in plating prior to the attachment of framing by welding, usually with the following restrictions: Rivets immediately adjacent to the weld (usually within 6 in.) are omitted, or these rivets are especially inspected after welding to detect any looseness, and redriven if necessary.



Objectionable detail — Correct detail

Fig. 6.—Hatch Corner Details

Since this leads to odd work at greater cost this practice to insure tight faying surfaces is sometimes expensive.

With regard to the general sequence of making the joints in an assembly of plating, deferring the riveting of a longitudinal seam for 12 in. both ways from a transverse butt weld, materially reduces any restraint arising from the fact that both plates are fully secured by riveting. Permission of the regulatory body concerned must generally be secured for each case where rivets and welds are to be used in combination and permission is generally granted only for comparatively unimportant structures or in cases where the butt welds are strapped or backed-up by other members, thus minimizing the possibility of weld cracks.

Although welding a transverse butt causes uniform bodily movement of a free plate, it is not always necessary to omit shop-punched holes, if the proper allowance for this shift is made in layout. Following the welding of the butt, the plate may then be well bolted and regular reaming and driving practice carried out. The usual requirement that transverse butt welds be made with one plate free therefore constitutes little handicap to the economical use of the combination.

Another disadvantage of the combination system is difficulty in maintaining watertightness where a riveted joint passes a welded watertight member. Since all riveted joints and plating must consist either of lapped or strapped butts, a seepage channel is provided past the welded member which must be closed. This is generally accomplished by slitting one part of the lap, or the strap, hand-welding this slit using a vee groove with sufficient root opening to insure penetration into the other member of the joint and thus providing an effective stop-water.

The overlap of plates or the presence of a faying flange on framing members requires a modification in plate-edge preparation for the welded joints where they cross riveting, to provide for welding from one side only.

WORKMANSHIP

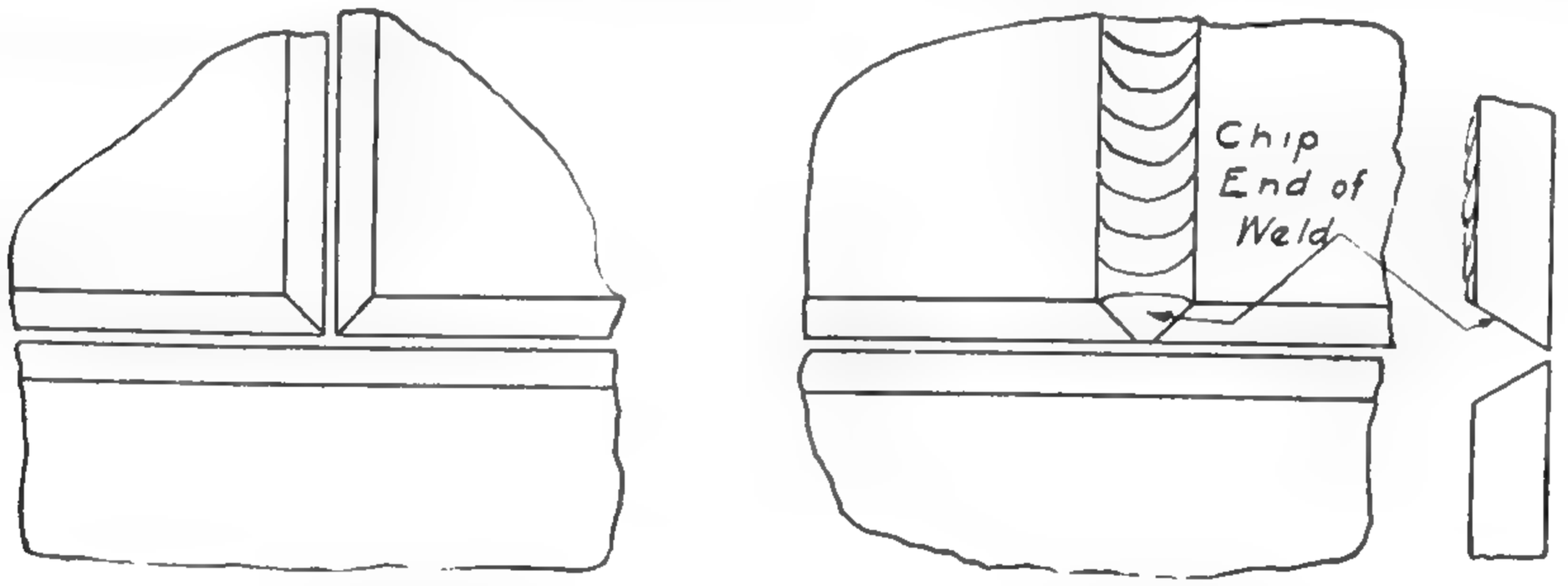
General

Workmanship is affected by so many factors that the term should not be restricted to refer only to the work done by the welder. Before welding, which is often the final operation, all the earlier steps must have been planned with due

regard to securing good workmanship if the best quality is to be obtained. The steps which precede welding are carried out by several other workmen, and the workmanship involved is as important to the ultimate weld as the deposition of metal.

To avoid difficulty in welding, the molds and templates should be accurate, the material cut or machined to close tolerances and the edges prepared to the correct bevel. Subassemblies and units should be made on well-supported floors or skids which will hold the intended shape. When completed they should be handled and stored with adequate care to prevent damage to prepared edges which must be made to match with adjacent structure later.

In all welds made from both sides, the root of the weld deposited from the first side should be cleaned out by oxygen gouging or chipping, and in this operation workmanship is of the utmost importance.



Before welding — Treatment of first weld

Fig. 7.—Welding at Intersection of Two Joints

The flame or tool should leave a semicircular groove into which weld metal can be deposited from the second side. The groove should be deep enough to expose solid weld metal and to remove all slag or dirt entrapped in the root of the first side.

A common source of defects in welds results from failure to chip the end of the first joint welded at an intersection. (See Fig. 7.) Although often omitted because a chipper is not readily available, proper preparation of the edges for the weld on the second side is essential.

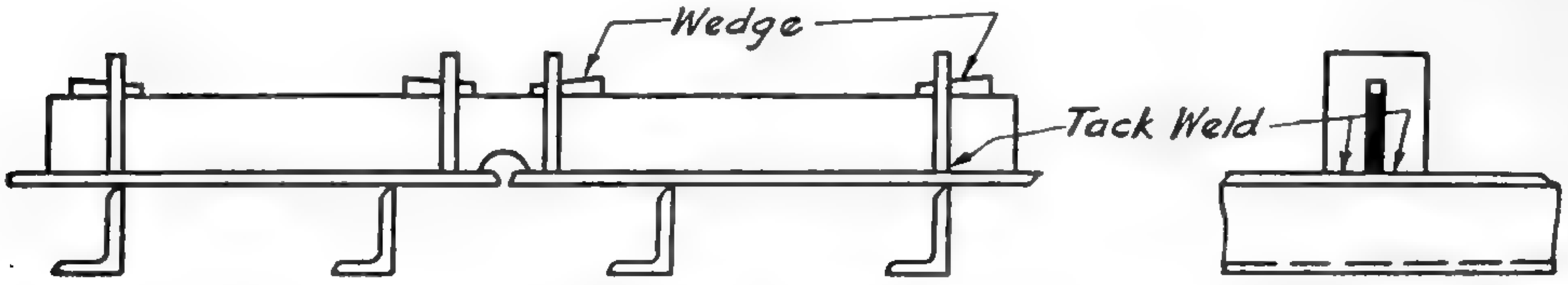
Fitting up the parts and assemblies on the shipways necessitates the use of tack welding and various fittings such as clips, strongbacks, etc. Apart from regulating and supporting the members in their correct positions, these should be arranged so as not to interfere with welding operations nor to restrain the parts too greatly against contraction from welding. Some freedom of movement should always be allowed. (See Fig. 8.) Tack welds should be removed or carefully fused to final welds and used no more than absolutely necessary. Cracked tack welds must be removed.

Preparation of joints on the shipways must often be done without the use of mechanical equipment, and the workmanship depends upon the skill of the cutters and chippers. Guiding devices for manual cutting are very effective when properly used. Errors, such as cutting beyond the correct end of a cut or chipping an irregular bevel or one which is too wide at the root, may cause conditions which result in defective welds. (See Fig. 9.)

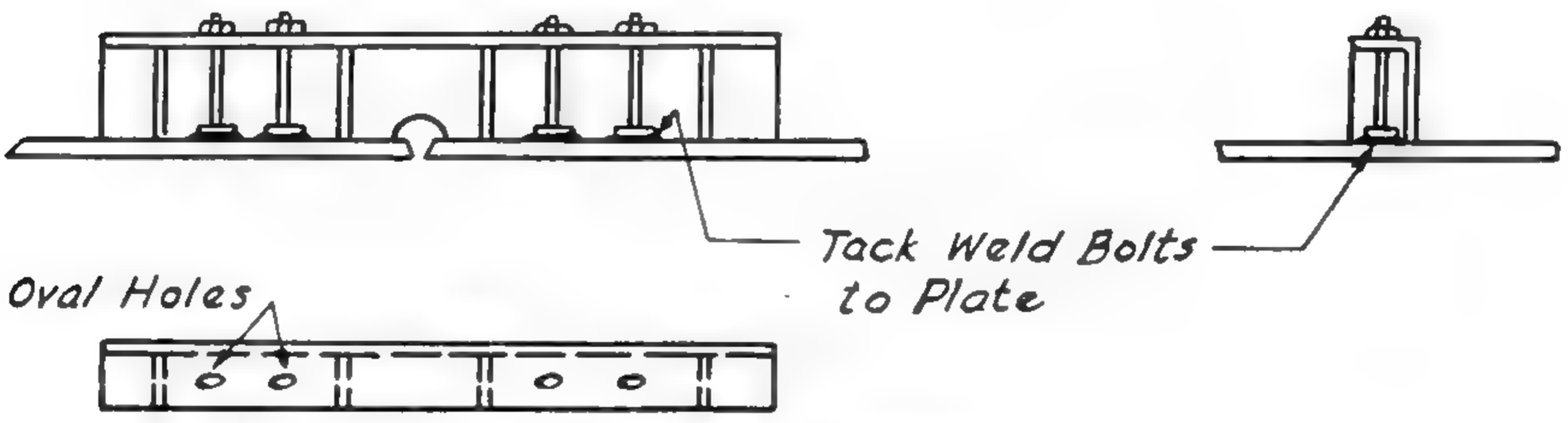
Given proper planning and preparation, a suitable procedure and adequate supervision, the welder himself should be considered. In ship work, qualification is established by satisfactory performance of tests adopted jointly by the U. S. Navy, U.S. Coast Guard and American Bureau of Shipping. To insure that the operator will perform the best work of which he is capable, the factors which may affect him personally should be taken into account. Positioning the work makes the welder more comfortable and less easily fatigued. This is important to a skill which depends so largely upon the dexterity of the operator. Adequate ventilation, especially in confined spaces, and good accessibility, are also requisites for comfort and con-

sistent good workmanship by men who must wear shields or helmets and heavy, cumbersome clothing.

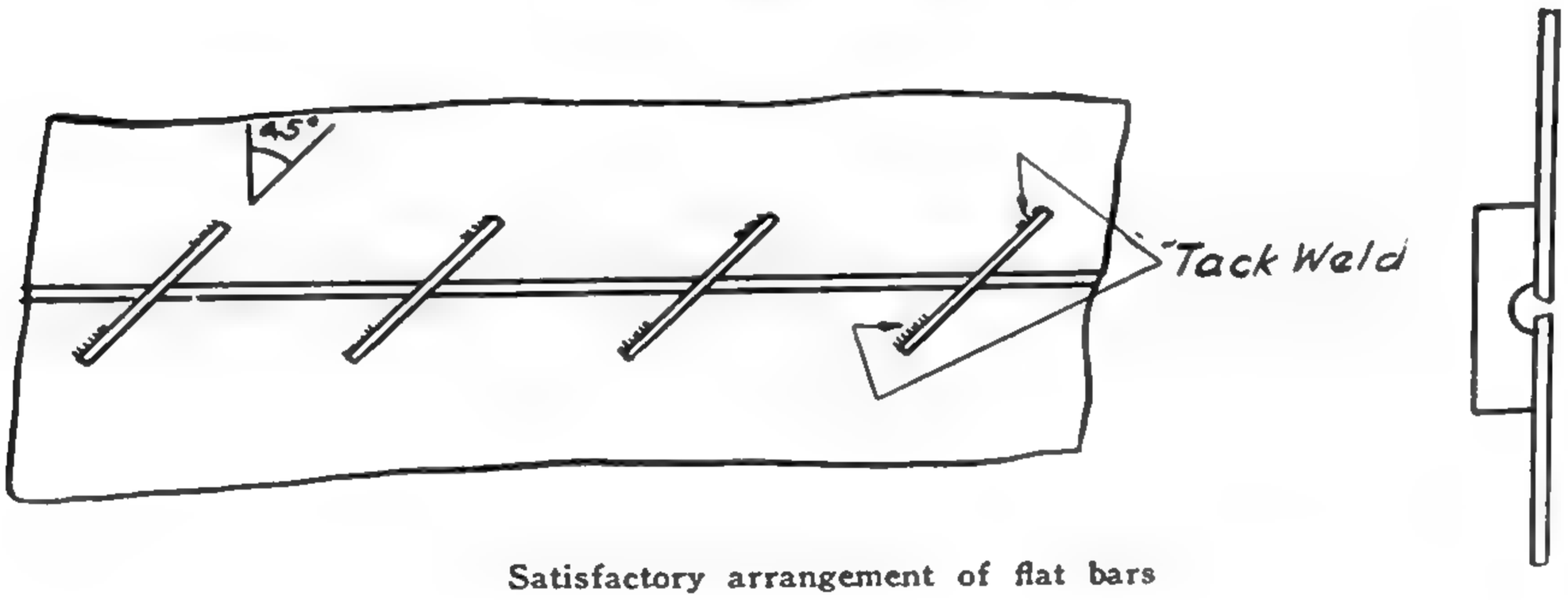
Electrodes properly stored, or conditioned if necessary, for correct moisture content in the coating, eliminate another variable which the welder may or may not be able to offset by departing from the prescribed procedure. Maintaining the welding machines or other power sources in good condition relieves the welder of the necessity of making his



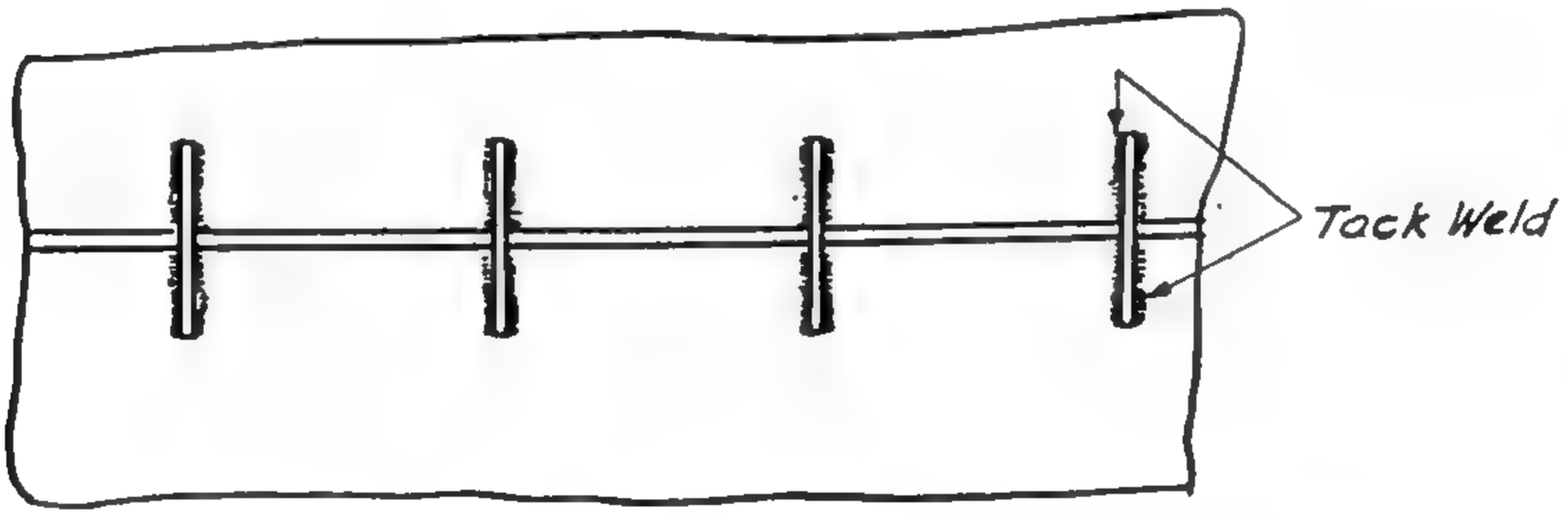
Floating strongback



Bolted angle strongback



Satisfactory arrangement of flat bars



Unsatisfactory arrangement of flat bars

Fig. 8.—Use of Strongbacks to Minimize Restraint

own corrections in the setting or otherwise adapting his work to an unsuitable current.

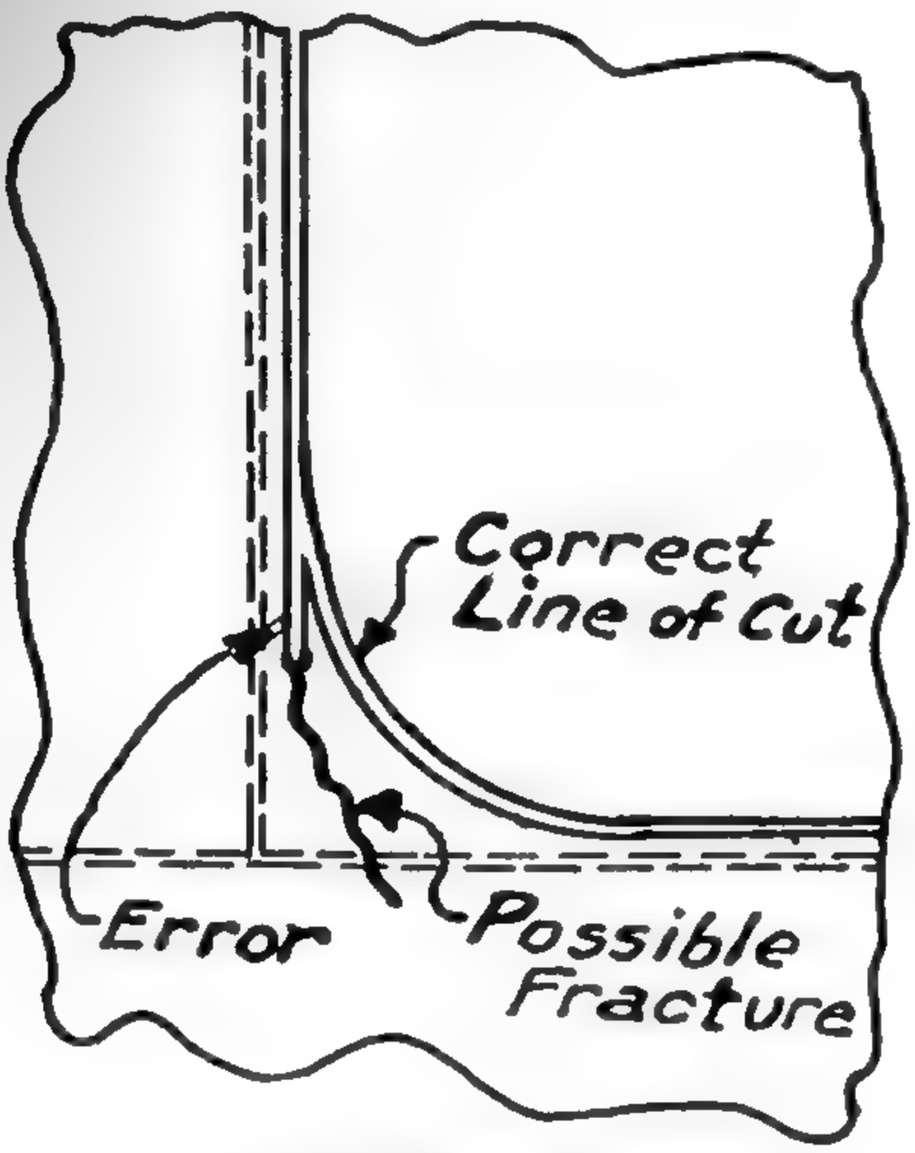


Fig. 9.—Notch Effect Produced by Cutting Error

Shelter from rain or wind not only adds to the comfort of the welder but often is essential to the welding operation itself.

The edges and surfaces to be welded should be cleaned to minimize the inclusion of foreign matter in the weld metal.

The more difficult and most important joints in the ship are often assigned to welders who specialize in one type of joint. Apart from the experience thus gained by the welders, the supervisors have the advantage of being familiar with the capabilities of these few men, and so can better control the quality of the work. However, a weld attaching even a small fitting to main structural strength members sometimes requires the same quality and soundness as the joints in the strength members themselves. Failure of an apparently unimportant weld has frequently led to fracture of deck or shell plates.

When errors have been made in cutting or fitting, they may be corrected if suitable methods are used and the mistakes not covered up. If the edge or end of one member does not meet the surface of a plate to which it should be welded, a liner may be used. (See Fig. 10.) In butt welds which cannot be made to fit up to the correct root opening, one or both edges of the plates may be built up using a temporary backing strip if necessary, before attempting to join the plates by making the butt weld. Where defective welding is removed, it is essential to prepare the ends of the cavity by chipping or gouging to form a groove suitable for sound welding which will merge into the existing weld.

Inspection is discussed elsewhere in this chapter. However, it should be mentioned that any one of the methods of subsurface inspection, although used only as a spot check, is effective in maintaining the quality of workmanship.

Caulking Over Cracks

There are still cases where an attempt is made to caulk leaky welds in both watertight and nonwatertight structures. This is a serious matter because it means that internal cracks are being covered up by bobbing the material over them and these cracks are being left in the structure as potential triggers for a subsequent structural failure. The practice of bobbing over cracks is justified only in very rare cases on structures which will not jeopardize the safety of the vessel if a failure should occur. For watertight work, particularly on the shell, this pro-

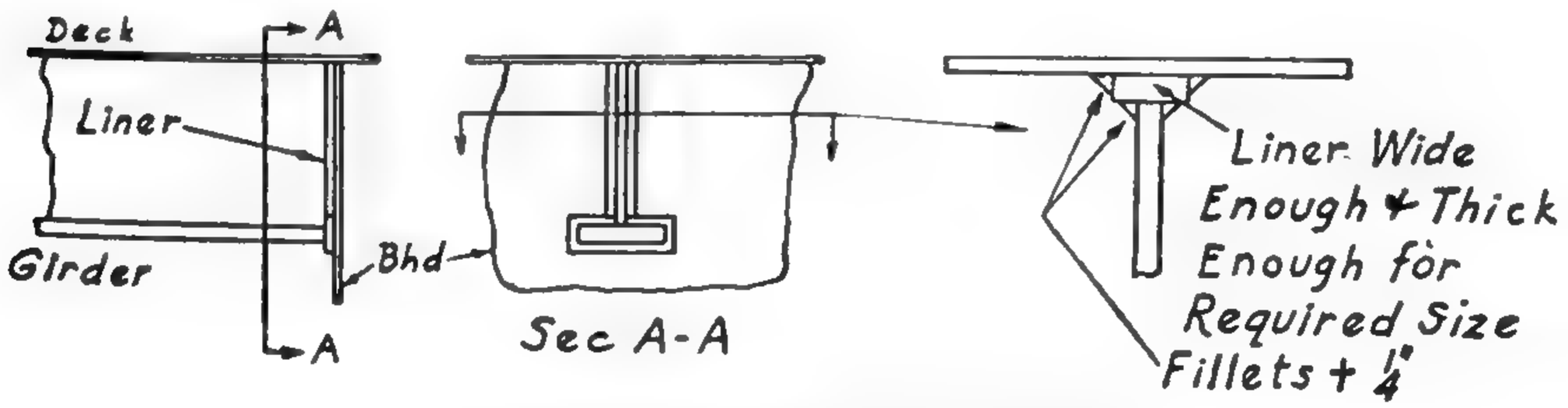


Fig. 10.—Use of Liner to Correct Poor Fit-Up

cedure is extremely dangerous and should be prohibited. Cracks in leaky welds should be carefully veed out by gouging or by chipping with a suitable round-nosed tool and rewelded.

Cracks which have been hidden by peening often lie partially dormant for weeks or months. While in this partially inactive condition, such cracks may grow under the influence of alternating stresses which accompany the motion of the ship in the seaway. Sooner or later, however, there may be an instant in which the material of the ship's hull is conditioned by temperature to encourage the propagation of a crack. When this instant arrives, a fairly moderate stress resulting from the ship's motion at sea or even from the distribution of cargo can be sufficient to cause the small crack to propagate rapidly into a serious failure. The danger of peening cracks therefore cannot be over emphasized.

Distortion and Cracking

Experience in the construction of welded ships and other large structures indicates that certain principles must be recognized in carrying out welding procedures and sequences if distortion and cracking are to be controlled.

Recent investigations of structural failures in welded ships have resulted in the conclusion that the locked-in stresses do not contribute materially to these failures and that longitudinal residual welding stresses cannot be altered by variations in welding procedures. These conclusions have been widely misinterpreted. The presence of locked-in stresses and shrinkage forces is not denied and the reports specifically caution that care must be taken with the welding procedure if cracking is to be avoided and distortion controlled. Furthermore, it is an established fact that reaction stresses perpendicular to the weld can be controlled by adjusting the assembly and welding sequence.

The participation of shrinkage stresses

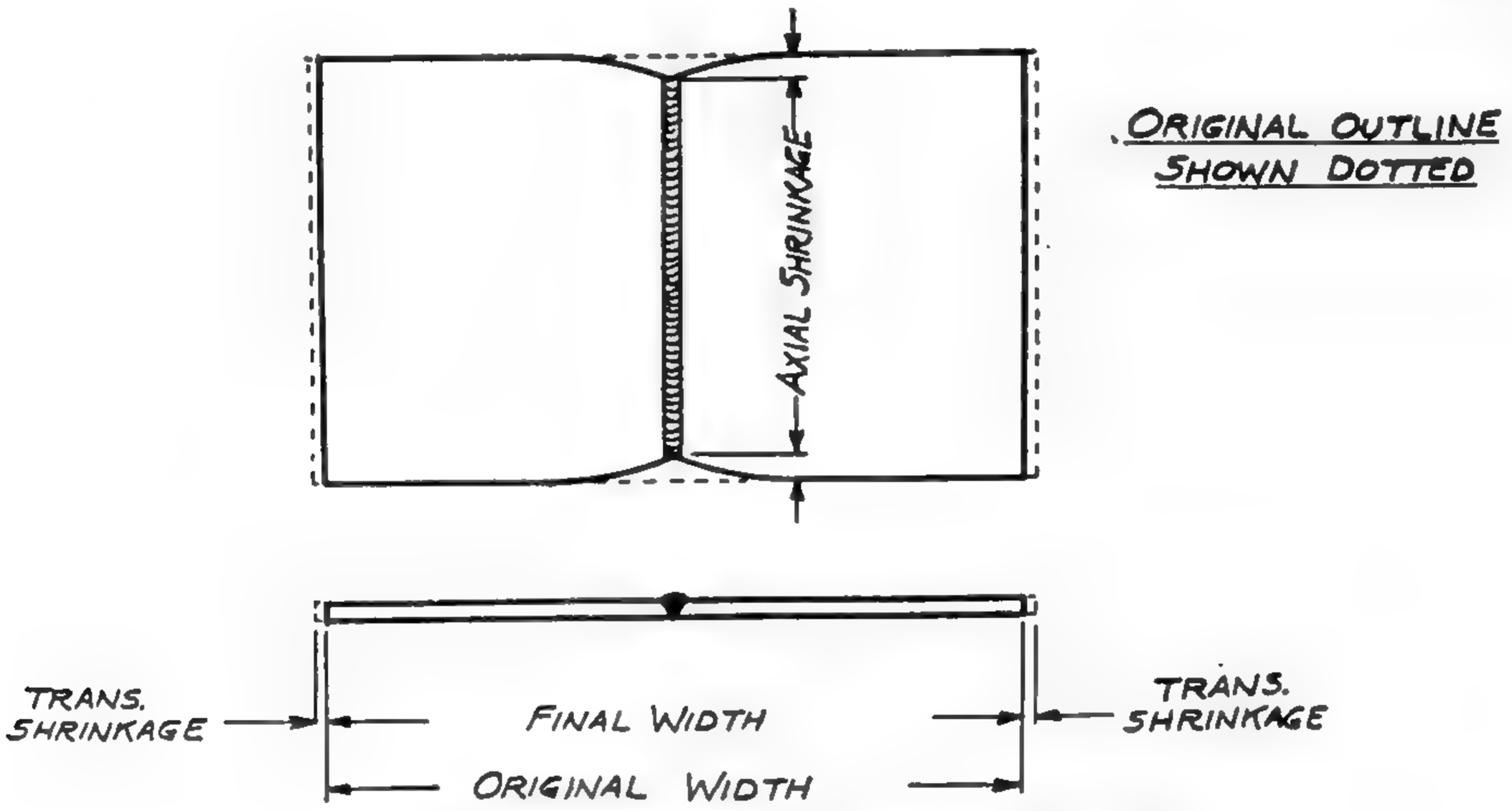


Fig. 11.—Shrinkage Effects of Cooling After Welding

NOTE: The same effects, to a lesser degree, are evident in fillet welding.

in the phenomena of cracking and distortion is not fully understood. For this reason, it is necessary to focus attention directly on the ultimate goal of control of distortion and cracking instead of the more elusive and unmeasurable shrinkage stress. It is by these tangible manifestations that welding procedure and sequence can best be evaluated.

A proper sequence of welding is one of the most important factors in carrying out the procedures to be followed. No simple rule, applicable to all cases, can be given. The objectives in setting up a welding procedure are threefold: (1) to avoid excessive restraint against weld

shrinkage, (2) to minimize distortion and (3) to facilitate the deposition of sound weld metal. These objectives are not always compatible and the welding engineer may have to seek a satisfactory compromise.

The weld metal and adjacent heat-affected zone of the base metal contract on cooling and tend to draw closer together as shown in Fig. 11. Mass, shape, structural attachments and previous welding may tend to prevent this shrinkage.

Table 2—Allowances For Shrinkage

Butt Welds

Transverse—1/16 to 3/32 in. for all thicknesses
Longitudinal
- Over 1/2 in. thick—1/32 in. in 10 ft.
- 3/8 to 1/2 in. thick—1/32 to 1/16 in. in 10 ft.
- 1/4 to 3/8 in. thick—1/32 to 3/32 in. in 10 ft.
- 1/4 in. and thinner—1/16 to 1/8 in. in 10 ft.

Fillet Welds

Tucking Allowance

- Over 1/2 in. thick—no allowance
- 3/8 to 1/2 in. thick—1/64 in. each stiffener
- 1/4 to 3/8 in. thick—1/32 in. each stiffener
- 1/4 in. and thinner—1/16 in. each stiffener

Developed for use on flat plates with continuously welded stiffeners. Intermittent welding will result in about one-half the tucking tabulated above, when the weld lengths and spacings conform to the requirements for shipbuilding.

To minimize these tendencies toward distortion in lighter plates or cracking in heavier ones, certain special techniques have been found to be effective. Skip, back-step, block and cascade welding, intermittent welding, pre-bending and peening, described in Chapter 43, have all proved beneficial under certain circumstances. Use of intermittent fillet welds, where feasible, is also effective.

Since shrinkage cannot be avoided altogether, allowance must be made for loss of dimension due to such shrinkage. The rules used by one shipyard are given in Table 2. In order to minimize shrinkage and distortion effects, certain general rules of welding sequence have become accepted on the basis of long experiences. These rules are based on the principle of welding toward free ends, or in the direction of greatest freedom. Particular attention must be paid to weld junctions. The one basic rule which should not be broken in this regard is illustrated in Fig. 12. The correct sequence is shown in (*a*) and the incorrect sequence and probable results are shown in (*b*). The application of this rule to plate sequence is shown in Fig. 13. It may be extended as shown in Fig. 14 almost without limit. When used extensively through the midship body, this sequence results in a marked tendency for the ship to rise from the keel blocks at bow and stern. This tendency may be relieved by welding a complete band around the ship and proceeding forward and aft limiting the completed welding by a vertical cross section instead of permitting the bottom to progress ahead of the upper deck. The use of subassemblies and panels described later facilitates this method.

Nearly all plated structures in shipbuilding are complicated by the attachment of frames, stiffeners, bulkheads, etc., to the plating. The extension of the general sequence in Fig. 13 to include this framing is given in Fig. 15. The general idea of this application is to permit most of the shrinkage to take place before the plates are tied together at their edges. On small plates, where this method becomes less practical, the complete framing may be welded in steps 3 and 7 of Fig. 15 instead of just the unwelded *cross-overs*. One advantage of this sequence of welding plates is that the framing may be welded independently of the butts and seams so long as the plates are not welded together. This permits a greater number of welders to be put to work and reduces overall time of welding.

All the illustrations shown so far have shown the butts staggered. When butts are in line, subassemblies can be welded complete in the shop. This permits trimming to the exact size after all shrinkage has taken place. These subassemblies are then treated as single plates as previously described. (See Fig. 16.)

If subassemblies cannot be made on the ground because of shape or other peculiarity, the sections can be welded as panels on the ship using the same idea. The seams or butts can be welded complete, with regard to local sequence, and all the framing to the panel welded complete to

within about 12 in. of all panel edges. Care should be taken that this welding is complete before the panels are tied-in at their boundaries. Both the seams and framing can be welded without regard to overall sequence provided this care is exercised. This permits large numbers of welding operators to be put to work without damage to the structure and since there are only a few tie-in welds to be made, the overall structure shrinks almost parallel to the base line and greatly reduces the tendency to rise at the bow and stern.

If the basic principle given in Fig. 12 is strictly followed and every effort made to obtain sound welds, cracking may be avoided. All the illustrations are merely extensions of this basic principle and are given to illustrate the simplifications which can be made with what seems to be a complicated structure. Attempts to break welding sequences into smaller individual steps lead only to such complicated practices that they cannot be followed in the field. The sequence should be simple and practical with steps large enough to permit a reasonable number of welders to work.

All of the foregoing rules pertaining to welding sequence may be summarized as follows:

1. Do not weld across an open joint.
2. Weld as much of the structure as possible in subassemblies before tying them into the ship.
3. Follow a sequence that will minimize distortion and insure good welds.

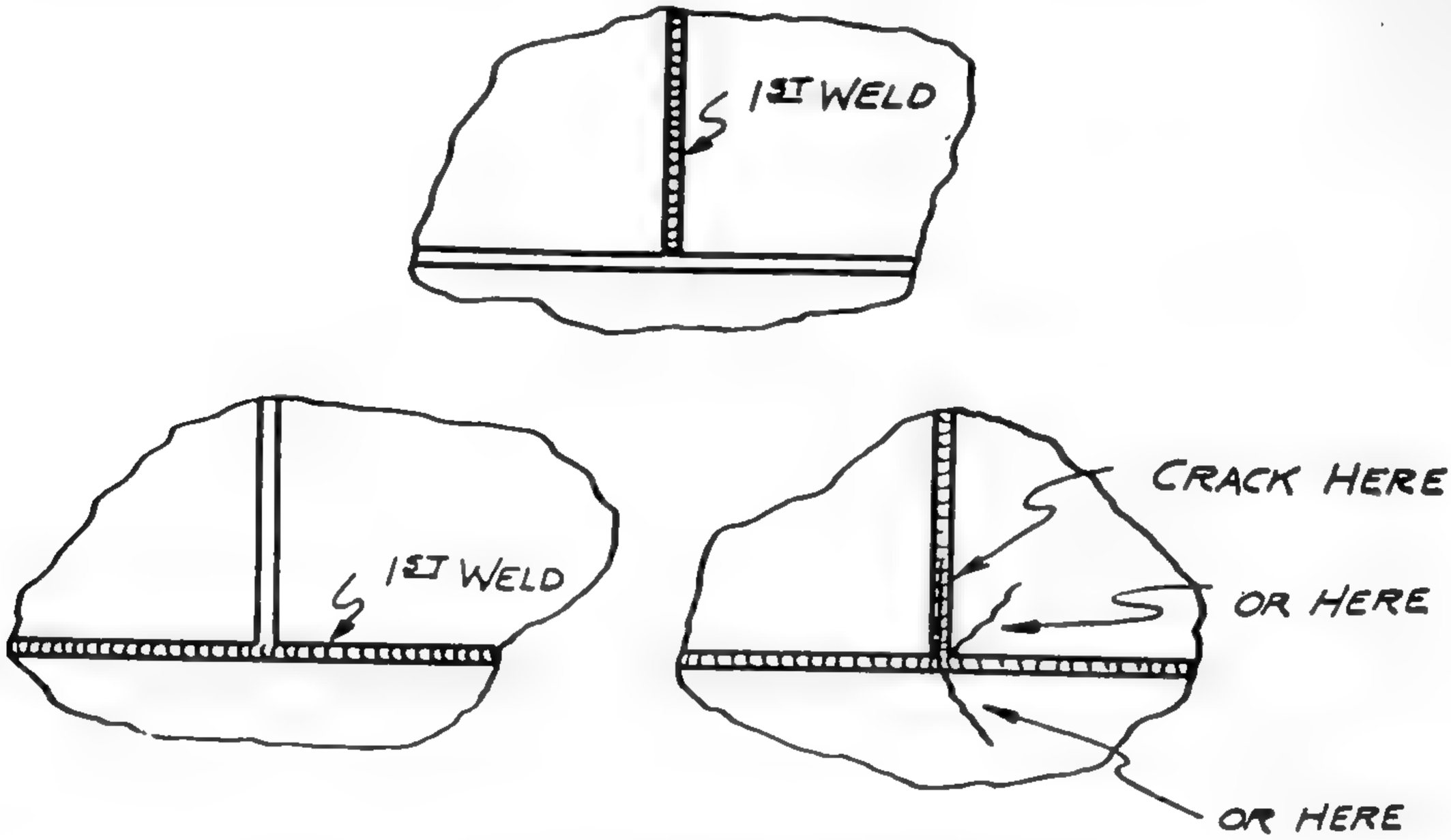


Fig. 12.—Sequence for Welding Junction of Two Joints

Top (a) Correct sequence
Bottom (b) Incorrect sequence (left) and probable result (right)

Fairing Tolerances

The following standards for the fairing of welded structures are reproduced from *Specifications for Welding, Part I—General* commonly known as Appendix 5—U. S. Navy:

"*Straightness of Structures.*—Where straightening of structure is required, it shall be postponed as long as practicable during the building period, so that one

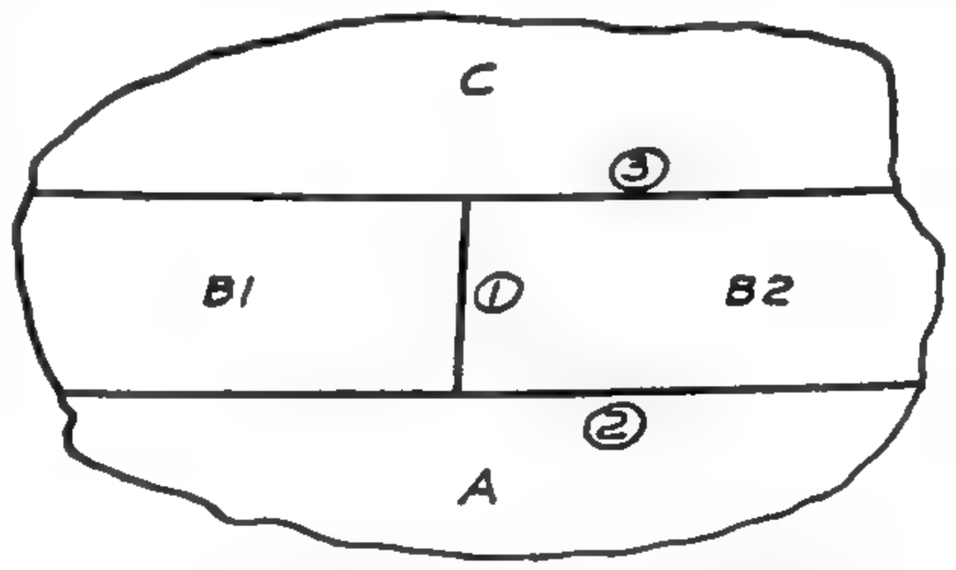


Fig. 13.—Proper Sequence for Welding Plating

1. Weld butt complete
2. Weld inboard seam complete
3. Weld outboard seam complete

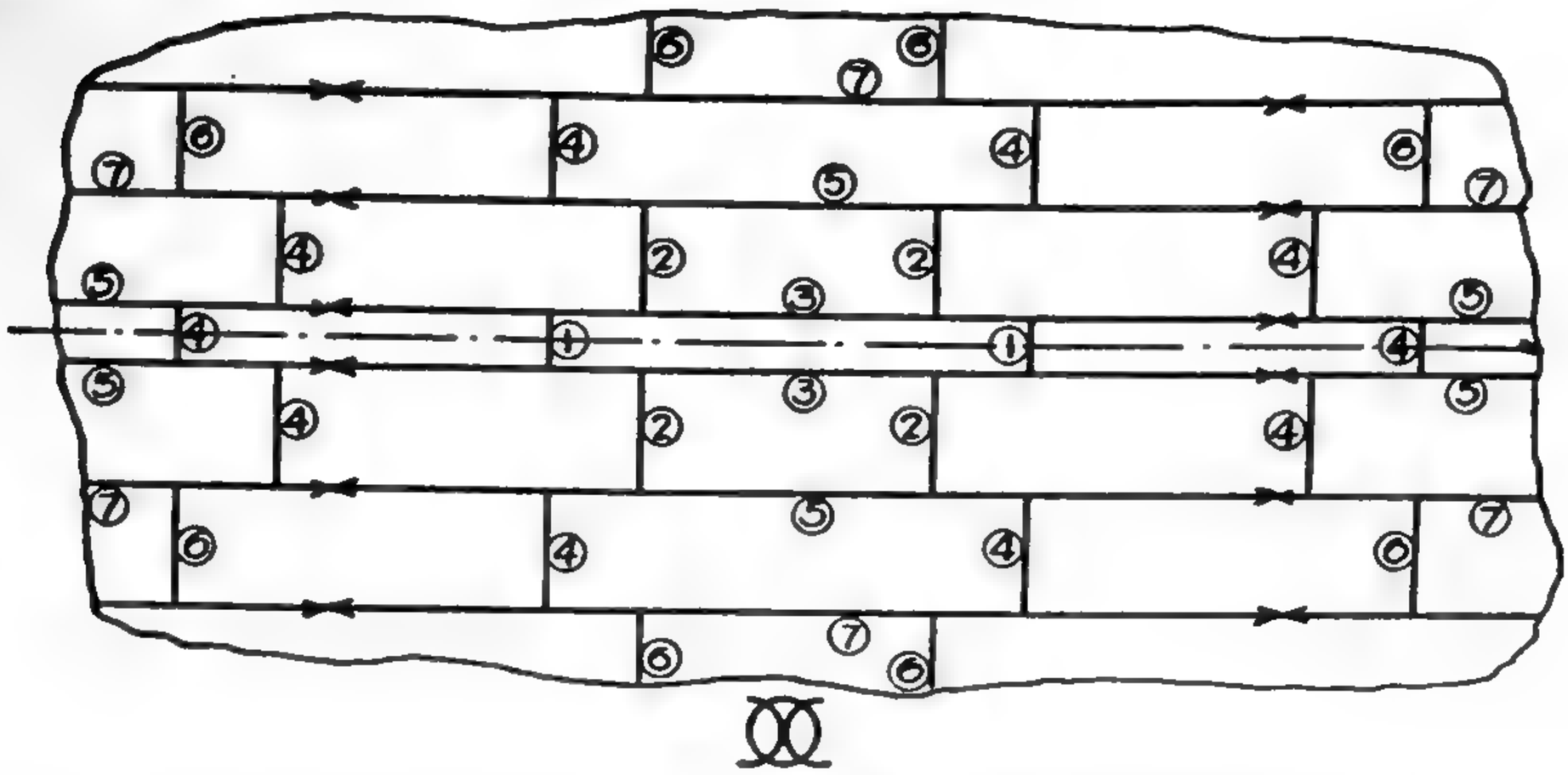


Fig. 14.—Proper Sequence for Welding Typical Bottom Shell

straightening operation will give the desired result. Where increase of cost will not result, straightening shall be delayed until the temperature of the structure to be straightened is at approximately the temperature that is to be expected under service conditions.

"In the interest of economy and to prevent surface marring of the structure, straightening of the plating shall be kept to a minimum.

"The unfairness of welded plating shall not exceed the tolerances shown in Fig. 17. In applying these tolerances, the unfairness of the plating shall be measured across the minor dimensions of the panel."

INSPECTION

Adequate supervision and inspection procedures are necessary in order to insure high quality workmanship. In the case of groove welds a considerable portion of this may be visual inspection of groove preparation, prior to welding. Root openings which are too small to

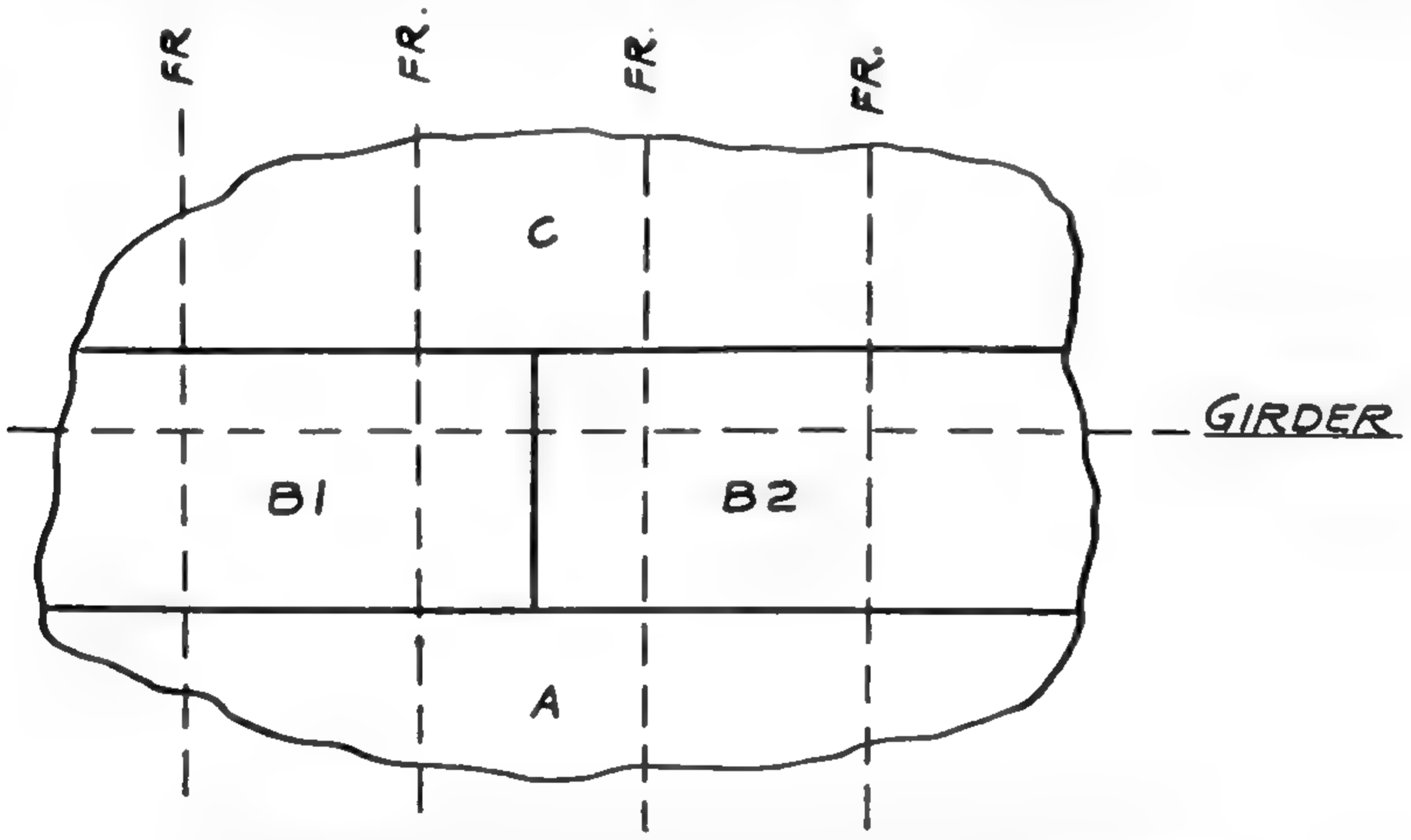


Fig. 15.—Proper Sequence for Welding Plating and Attachments

1. Weld frames and girder to plates to within about 12 in. of all unwelded butts and seams
2. Weld butt complete
3. Weld unwelded portion of girder in way of butt
4. Weld inboard seam
5. Weld unwelded portion of frames in way of inboard seam
6 Weld outboard seam
7. Weld unwelded portion of frames

permit complete penetration at the root are likely to result in inadequate gouging, back chipping and incomplete fusion of the finished weld. Root openings which are too wide may also be the cause of unsatisfactory welding if the sides of the groove are not built-up with care before bridging across the opening. After welding is completed, visual inspection is only effective in determining acceptabilty of weld contour, undercut, etc., and under some conditions a more searching means of inspection may be desirable to check the weld quality throughout the joint.

The principal means of inspection of finished welding which are currently employed in shipbuilding are trepanning, probing, radiography and magnetic particle inspection. Limited use has been made of recently developed ultrasonic inspection equipment.

to the surface. It is unreliable for subsurface inspection. See Chapter 42, Inspection of Welding for a more detailed discussion of these inspection methods.

The more serious types of defects which are likely to be found by trepanning or radiography are cracks, incomplete fusion and excessive slag. These defects are not only serious in themselves as a common cause of weld cracks but they may also provide seepage channels which destroy watertightness. Radiographic examination is not always efficient in detecting cracks. This should be borne in mind when judging the acceptability of welds by radiography. For this reason, magnetic particle inspection is frequently used in conjunction with radiography when the presence of cracks is suspected.

When defects of an unacceptable nature, as determined by the governing

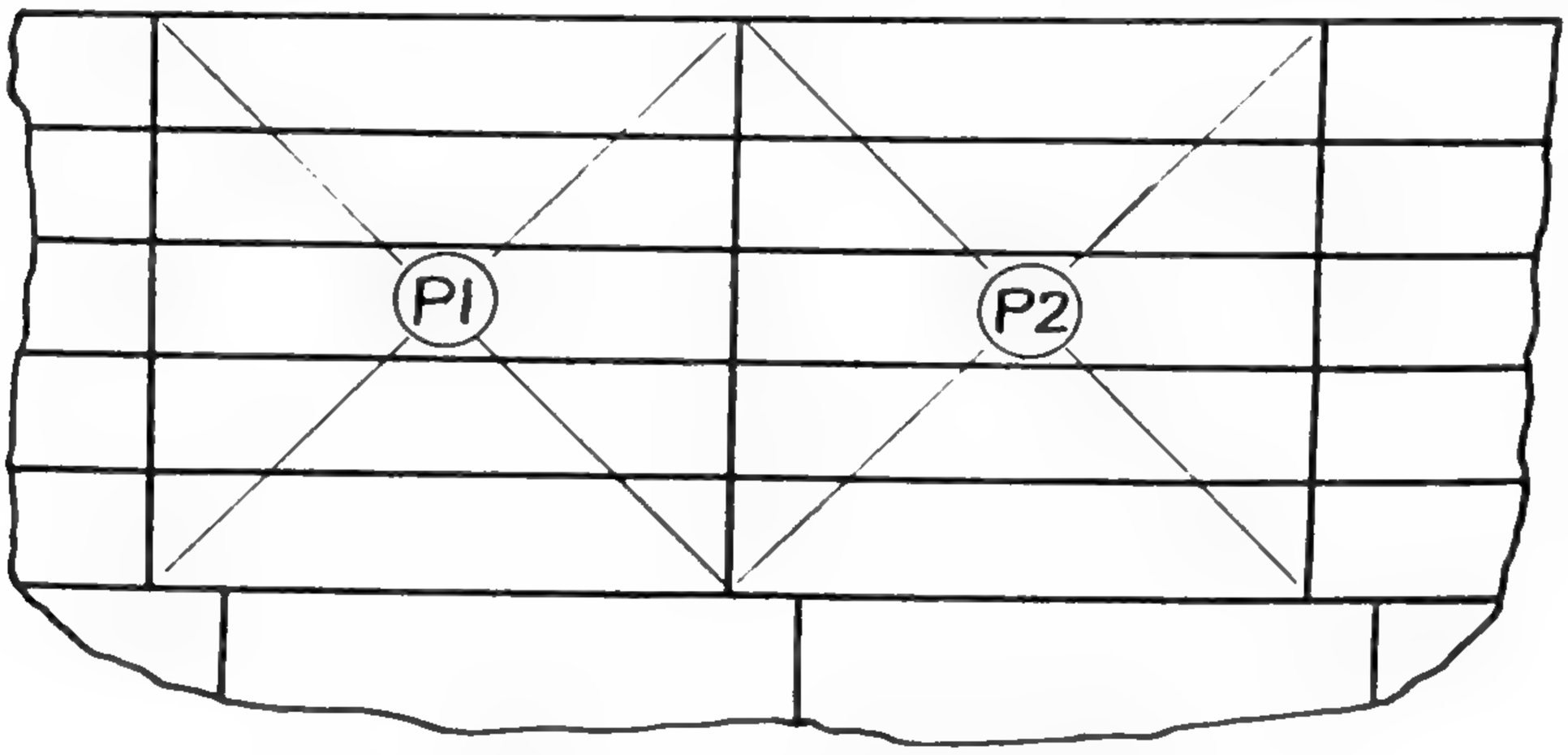


Fig. 16.—Proper Sequence for Welding Side Shell

1. Weld seams in panels P1 and P2
2. Weld all framing to within 12 in. of panel edges
3. Treat panels as individual plates in overall sequence

In the trepanning method, a sample of the weld is cut from a selected area and a cross section of the weld is prepared for macroscopic examination. In radiography a shadow picture of the weld is obtained on a film exposed to gamma rays (radium) or X-rays. The advantages of this method are that it examines a larger sample of the weld (usual film length is 10 to 17 in.) and, if the inspection proves the original weld to be sound, no repairs to the welding are necessary . The magnetic particle method is essentially limited to defects extending

standard, are located, it is necessary to remove the defective weld metal and reweld. The weld metal may be removed by oxygen cutting, oxygen gouging or by chipping, depending upon the amount of removal involved. Removal of the defects to their full extent is usually checked by magnetic particle inspection of the excavation, and the adequacy of the final repair is determined by sample radiographs.

Regardless of the relative merits of the method used for internal inspection of the welds it has been adequately demon-

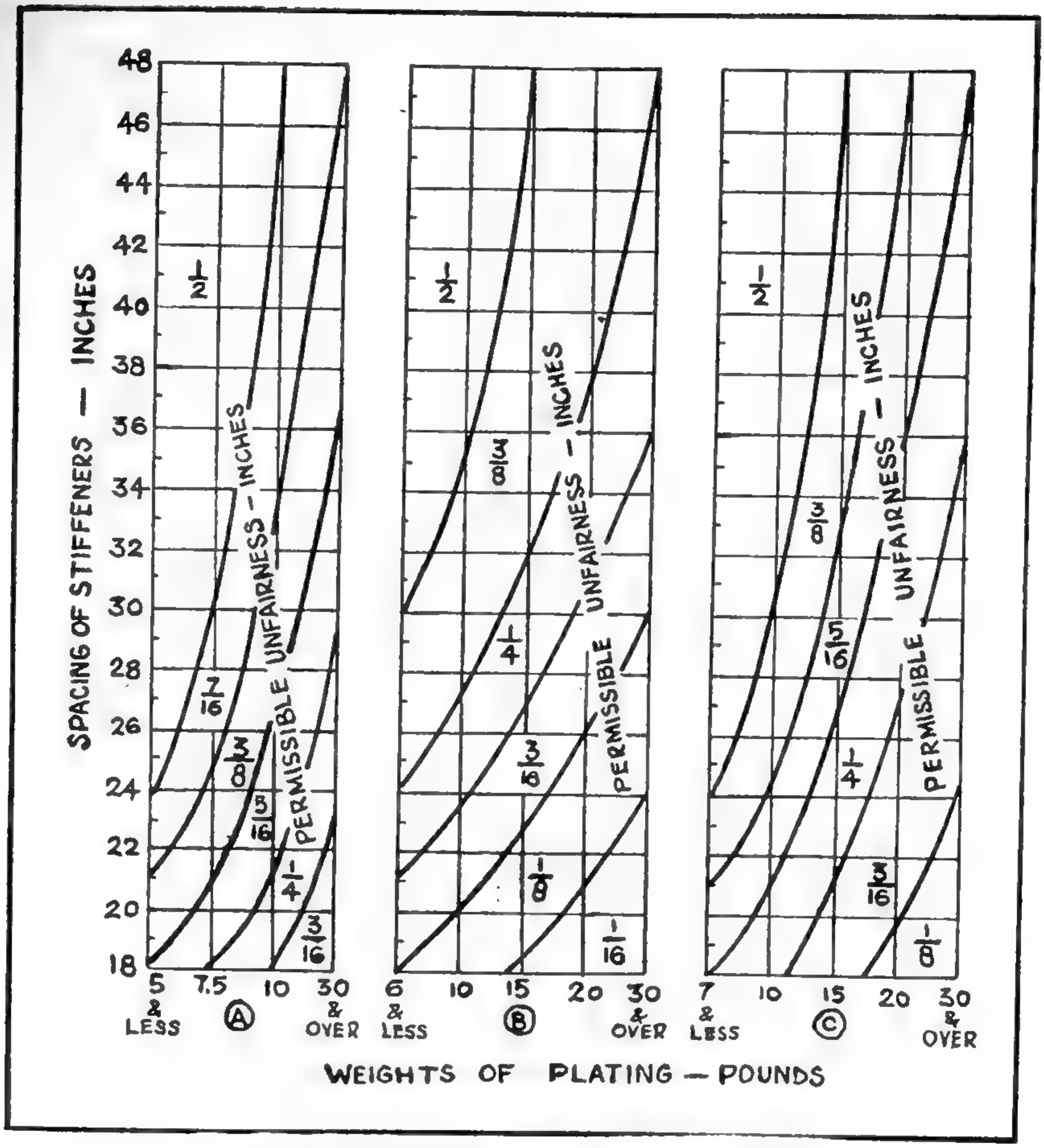


Fig. 17.—Tolerance for Fairness of Welded Structures

A. To be used on living quarters and longitudinal bulkhead plating. In other bulkheads unfairness of 1 in. per panel width will be permitted.
B. To be used on deck plating.
C. To be used on shell plating.

strated that the benefits are threefold. First, an effective inspection method is provided. Second, the psychological effect of introducing inspection equipment into the shop and on the shipways results in an immediate general improvement in the quality of welding. Third, an overall economy in construction results if the quality of welding is maintained at a high level.

Although only a comparatively small percentage of the total footage of welding is checked, several of the wartime shipyards reported that their welders took greater care in making welds when they knew there was a possibility that the welds might be radiographed or probed. Most of the yards attributed as much as 90% of the benefit of subsurface inspection to the psychological influence on the welders. Of course this substantial benefit cannot be achieved unless each weld is identified with the welder so that a quality incentive plan can be associated with the subsurface inspection.

Normally a certain amount of weld rejection and replacement can be expected on the basis of surveys made by inspectors of prospective owners and classification societies. This removal and re-

placement is very costly. The increased quality which results from the introduction of subsurface inspection reduces the weld replacement loss. Most shipyards reported that the saving on replacement cost, more than offsets the cost of the inspection. No measurable decrease in the overall weld production rate was found after the subsurface inspection system had achieved an accepted position in shipyard routine.

REPAIR INSTRUCTIONS

The repair work to be done on the hull structure should be carefully studied and a procedure for doing the work laid out in advance. In making repairs the following points should be kept in mind, to assure that proper techniques are used:

1. The fractures in hull plates, etc., usually start at localized concentrations of stress. In the preliminary inspection, the first thing to be determined is whether or not the fracture started in a notch or sharp angle (stress raiser), and if it did, to provide for the elimination of this feature.

2. When large breaks have occurred and where considerable material is to be removed and new plates, frames, etc., are to be inserted the repairs may possibly involve appreciably more restraint with less latitude for proper welding and direction sequences than in new construction so that careful planning is absolutely essential.

3. In the repair of cracks in the plating of vessels where it is not intended to add new material, somewhat different conditions prevail and the following should be observed:

(*a*) Locate the ends of the crack and at a point not less than one plate thickness beyond the apparent end of the crack drill a hole of diameter about equal to the thickness of the plate.

(*b*) After veeing out, if a crack has a root opening too wide for closing with the first bead, build up the crack with light beads, until a standard joint is prepared, then weld up as usual.

(*c*) In general, material should not be removed unless the crack has opened up to a large extent or there is definite evidence of deterioration or poor quality in the fractured plate. The fact that the plate cracked should not be taken as prima facie evidence that the steel is inferior in quality to other parts of the structure.

4. When possible, repair welding should be avoided in cold weather, particularly when the temperature is below freezing. However, the effects of cold weather may be overcome by preheating to about 150° F., before welding. Heavy sections should be preheated prior to making a repair, regardless of the ambient temperature. A tent or shelter should be used to protect the welder and the work from bad weather, and the arc from strong winds, and should always be used when the temperature falls below zero.

BIBLIOGRAPHY

1. *Principles of Naval Architecture*, Vol. 1, Chapter VI, Strength of Ships, David Arnott, Society of Naval Architects and Marine Engineers, 1939.

2. *Distortion and Shrinkage Problems in Ships and Other Large Structures*, LaMotte Grover, The Welding Journal, October and November 1942.

3. *Control of Welding in Shipbuilding*, LaMotte Grover, The Welding Journal, April 1943.

4. *Shrinkage Distortion in Welding, A Review of the Literature to January 1, 1937*, W. Spraragen and G. E. Claussen, The Welding Journal Res. Suppl., July 1937. *January 1, 1937 to January 1, 1944*, W. Spraragen and M. A. Cordovi, The Welding Journal Res. Suppl., November 1944.

5. *Supervision of Welding in Shipbuilding*, American Bureau of Shipping, 1944.

6. *Shipyard Welding Workmanship, NAVCG 137*, U.S. Coast Guard, U.S. Navy, Bureau of Ships, U.S. Maritime Commission and the American Bureau of Shipping, Government Printing Office, 1945.

7. *Radiography in Shipbuilding*, E. F. Tibbetts, Society of Naval Architects and Marine Engineers, New England Section, April 1946.

8. *The Design and Method of Construction of Welded Steel Merchant Vessels—17 July 1946*, Government Printing Office, 1947. Reprinted in The Welding Journal, September 1944, January 1946, July 1947.

9. *The Shrinkage and Distortion of Welded Joints*, F. Guyot, The Welding Journal Res. Suppl., September 1947.

10. *Tests of Various Designs of Welded Hatch Corners for Ships*, E. Paul DeGarmo, The Welding Journal Res. Suppl., February 1948.

11. *Technical Progress Report of the Ship Structure Committee, 1 March 1948.* Reprinted in The Welding Journal Res. Suppl., July 1948.

12. *Shipyard Management for Welding, CG 180*, Prepared by U.S. Coast Guard, U.S. Navy Bureau of Ships, U.S. Maritime Commission, and the American Bureau of Shipping.

13. *Welding and Allied Processes*, Chapter 92, Bureau of Ships Manual, Government Printing Office, 1949. (For sale by the Superintendent of Documents.)

CHAPTER 53

RAILROADS*

LOCOMOTIVE CONSTRUCTION

Codes

THERE ARE NO generally applicable codes covering welding as applied to the construction of new locomotives except the ASME Boiler Construction Code, Section III, *Rules for Construction of Boilers for Locomotives*, and certain requirements of the Federal Bureau of Locomotive Inspection pertaining chiefly to welding on safety appliances.

Applicable Specifications

The application of welding to locomotive boilers has been retarded by legal regulations, but recently progress has been made, under suitable safeguards, and a number of all-welded locomotive boilers are now in service. The details of the design and construction of boilers are covered in Chapter 51. It is sufficient to point out here that the principal reason for desiring an all-welded boiler was to find a solution to the problem of cracking in the riveted joints of high pressure boilers. Such cracking led to excessively high maintenance costs as well as to tying up badly needed locomotives.

Welding as applied to locomotive construction is confined chiefly to plain carbon steel plates or steel castings. The plates may be of firebox, flange or structural steel purchased to AAR Specifications M-115-47 or M-116-45 for such materials. Some alloy and other special steels are in experimental use. None of these steels can be subject to objectionable hardening in the heat-affected zone when welded without preheating. Similarly, steel castings are generally purchased to AAR Specification M-201-46 and with few exceptions can be welded without special handling. For the details covering the proper methods of welding any particular type of steel, the chapter relating to that material should be consulted.

Processes

Shielded metal-arc welding is used for the bulk of the welding in locomotive construction. Covered electrodes, as covered by AWS-ASTM *Specifications for Mild Steel Arc Welding Electrodes* and *Specifications for Low-Alloy Steel Arc-Welding Electrodes* are normally used (see Chapter 38). In recent years submerged arc welding has been used to a limited extent in constructing welded boilers.

Design Considerations

The use of welding on steam locomotives has not resulted in any extensive changes in design other than the change from riveted to welded joints. Certain design changes have been made concurrently with the adoption of welding, but not due primarily to the use of welding. No generally applicable statistics are available from which comparisons can be made of cost of welded vs. riveted construction in locomotives and tenders. It is certain, however, that welding has effected large reductions in the amount of repair work required. Economies in operation due to the elimination of leakage at the joints in fireboxes have resulted, and the elimination of leakage has in turn been one of the important factors contributing to improved performance of the steam locomotive, longer locomotive runs and more intensive use.

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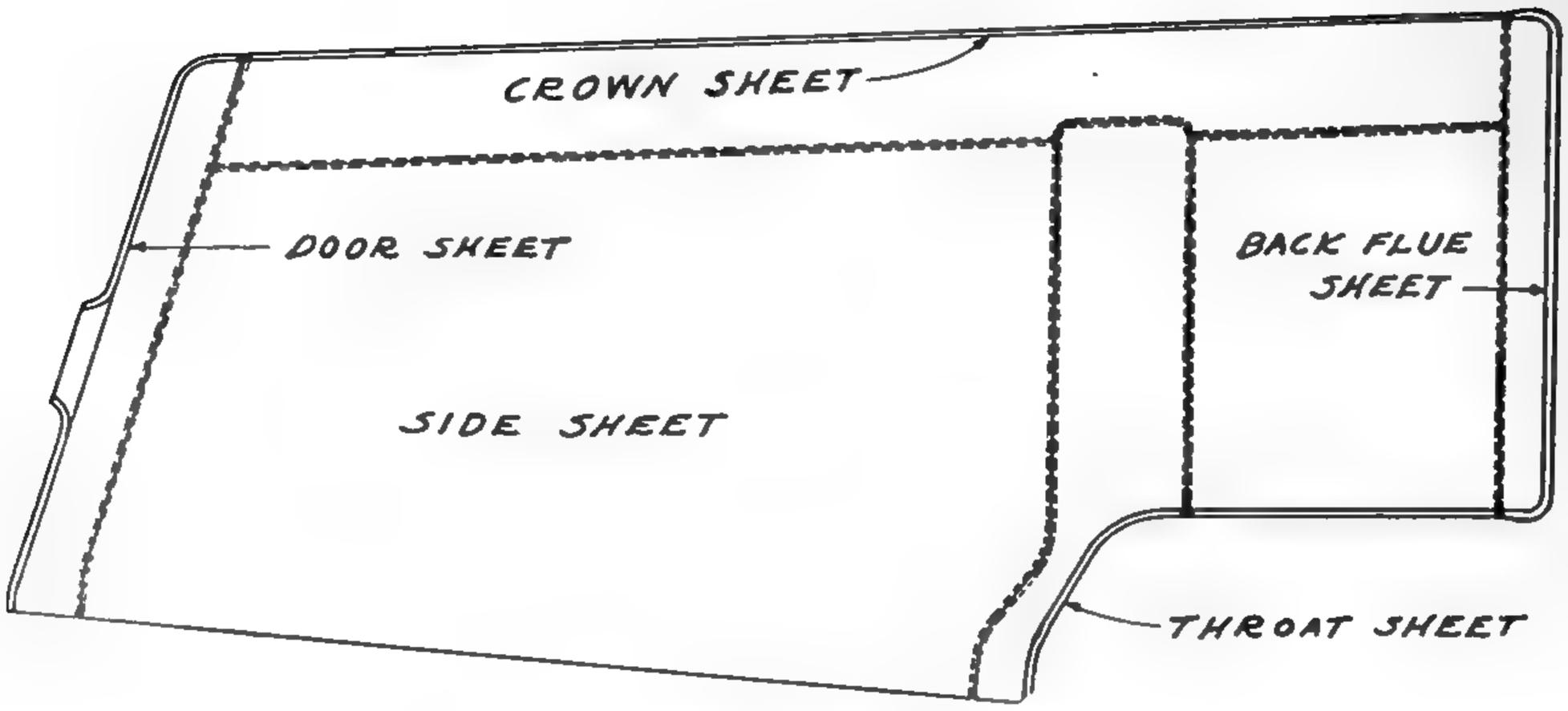


Fig. 1.—Typical Welded Firebox

Fireboxes

Construction.—Lap joints, welded on the fire side only, were at one time common in firebox construction, but in present practice only butt joints have been used. In new construction, and in repairs where practicable, all joints, except the one at the door-hole flange, are welded from both the fire and the water sides; single-vee groove welds are applied on the fire side after which the root is chipped out on the water side of sufficient depth to remove all flaws, and rewelded to provide complete penetration. Figure 1 shows a typical completely welded firebox and combustion chamber with a one-piece crown sheet. In some construction the crown sheet is in two pieces with a transverse weld joining the section comprising the top of the combustion chamber with that over the firebox. Another variation makes use of a continuous sheet for the sides and crown. Several railroads rivet the crown sheet to the flue and door sheets and the joints, after caulking, are seal welded in some instances.

Door.—Figure 2 shows the firebox door hole flange of the back head. Another method of designing this joint is to lap the flanges and apply a fillet weld around the circumference. The first method is generally preferred.

Tubes and Flues.—After the fire tubes and superheater flues are applied in the firebox flue sheet in the conventional manner by prossering, rolling and beading, the beads are usually seal welded as shown in Fig. 3.

Syphons.—Butt joints welded from both sides using a double-V groove are generally used for attachment of the flanges

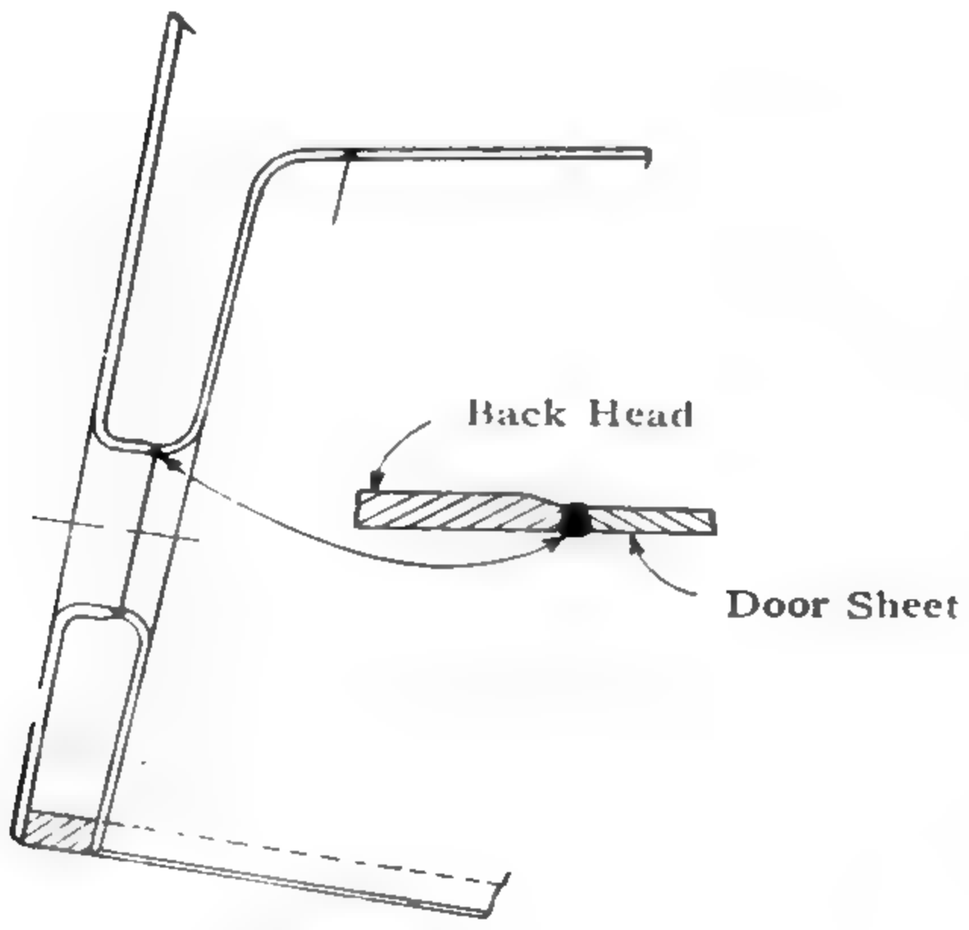


Fig. 2.—Typical Method of Joining Door Hole Flanges

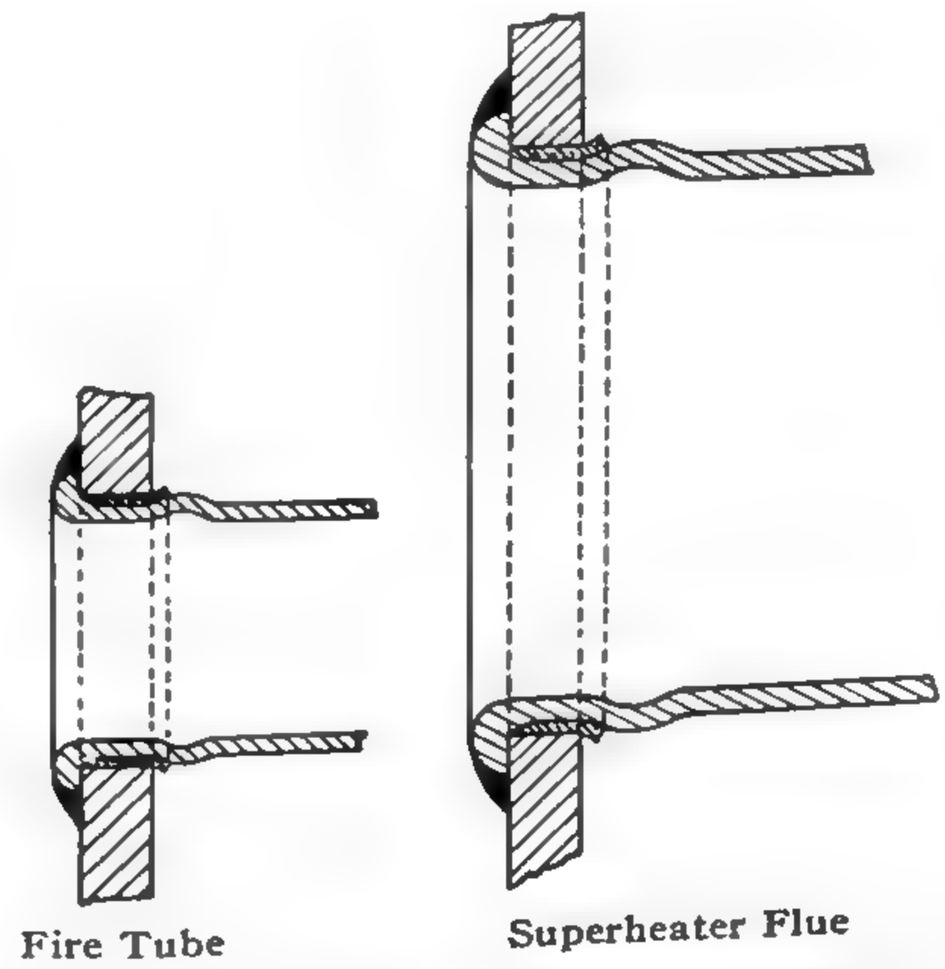
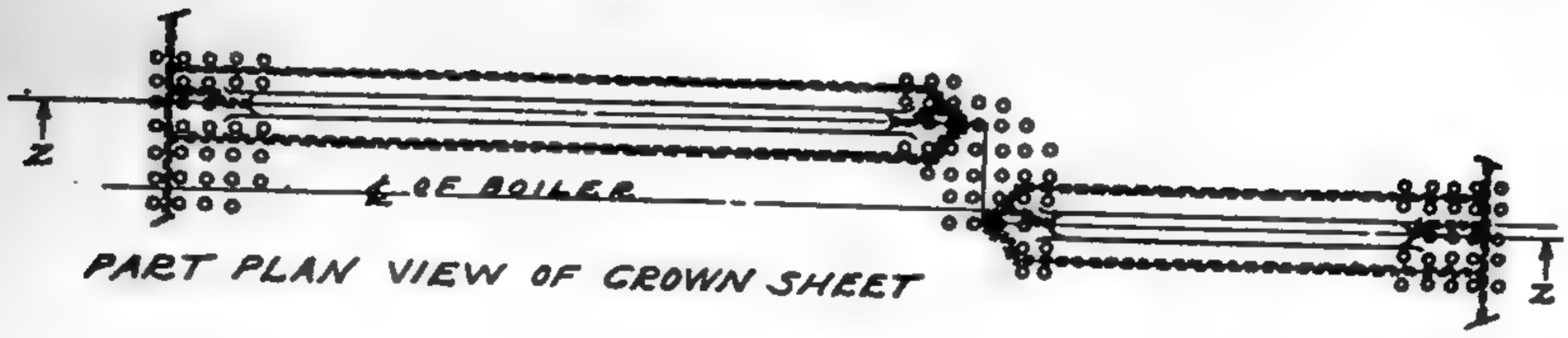
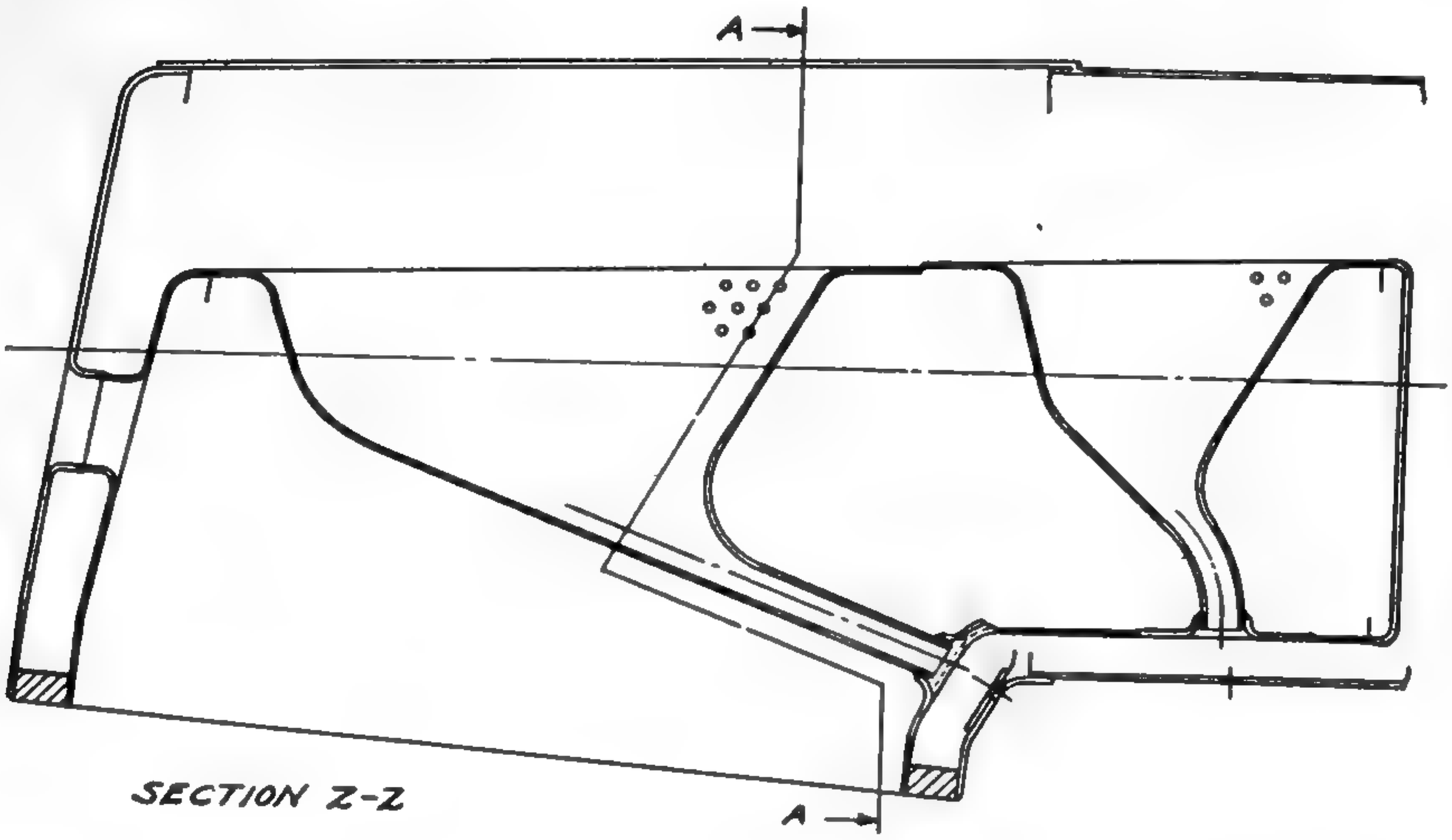


Fig. 3.—Seal Welding of Beads of Fire Tubes and Superheater Flues to Back Flue Sheet



PART PLAN VIEW OF CROWN SHEET



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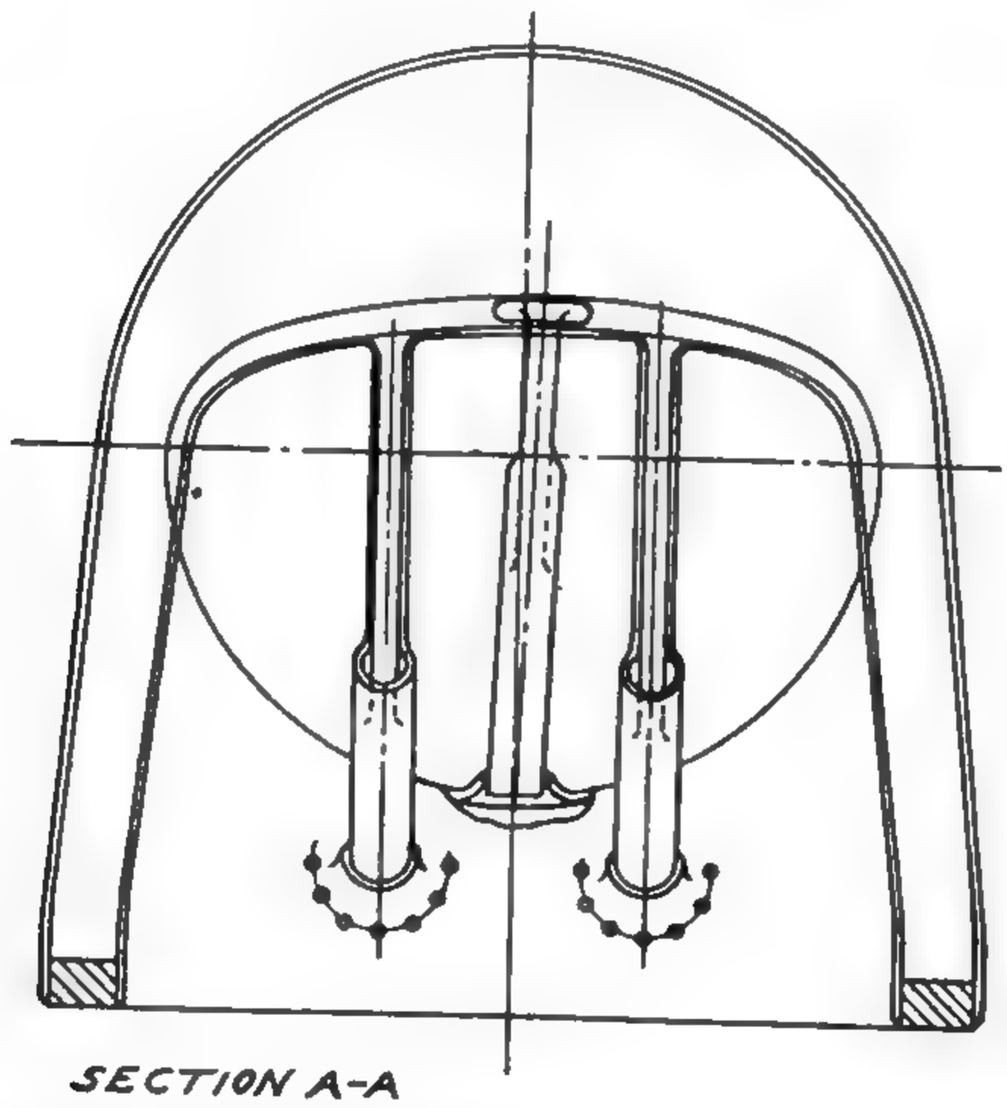


SECTION A-A

Fig. 4.—Conventional Installation of Syphons in a Firebox and Combustion Chamber

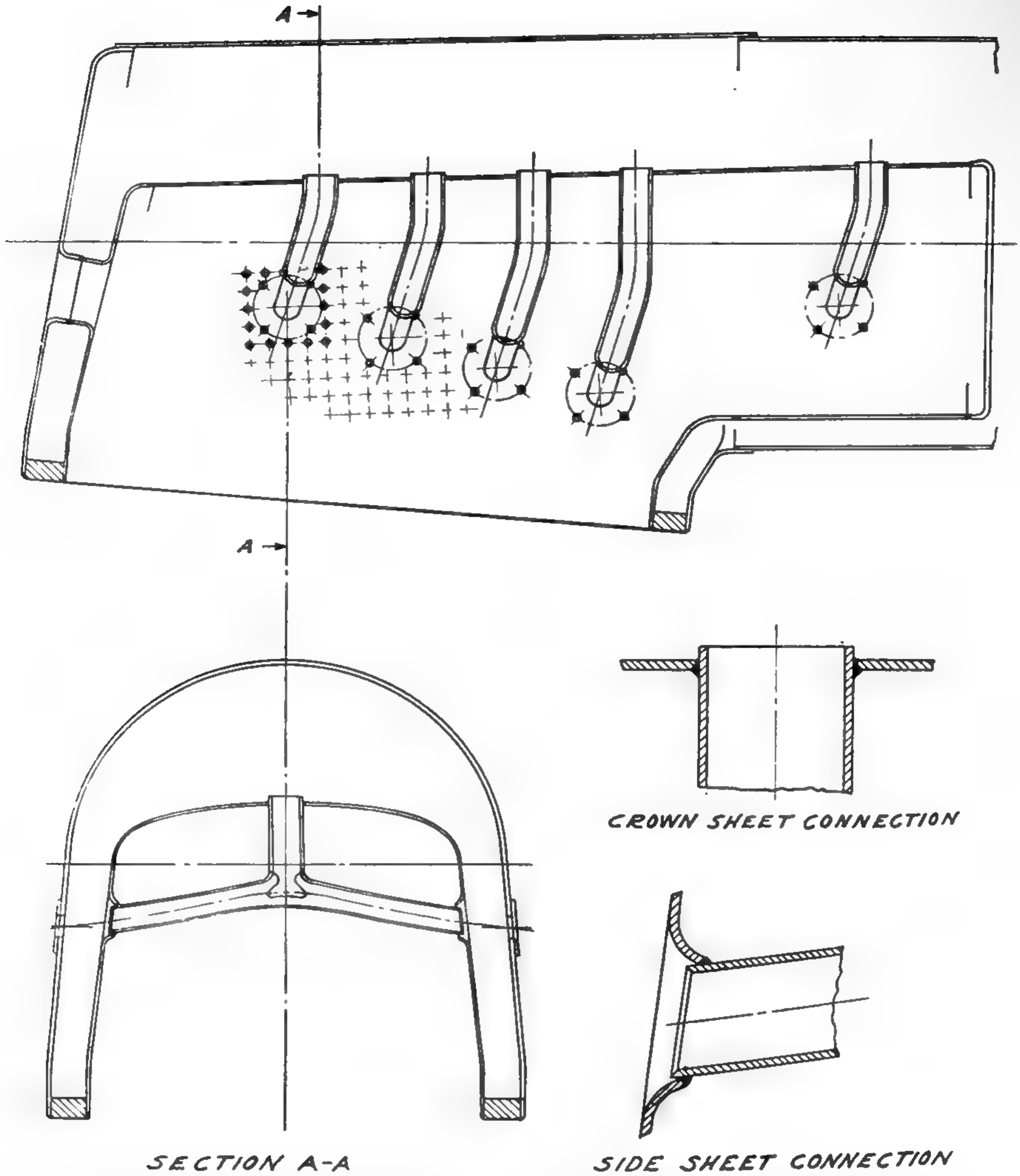


Fig. 5.—Conventional Installation of Circulators in a Firebox and Combustion Chamber

of syphons to the crown sheet except in instances where the installation is made in existing fireboxes in which event single-vee groove welds are sometimes used with the welding applied from the fire side. Fillet welds are used at the neck connection to throat sheet. A conventional installation of syphons in a firebox and combustion chamber is shown in Fig. 4.

Circulators.—A conventional installation of circulators in a firebox and combustion chamber is shown in Fig. 5.

Boiler Shells.—Welding is limited on the shells of conventional riveted-type locomotive boilers to preclude applications on unstayed parts, unless the part to which the welding is applied is supported by other construction that will maintain the required factor of safety. The principal uses of welding on riveted boiler shells are:

Seal Welding.—The abutting edges

of shell plates of joints having inside and outside butt straps are welded at the ends for tightness as shown in Fig. 6. The outside and inside firebox sheets are seal welded to the firebox ring at the corners after caulking; and seal-welding is applied after caulking, to the joints of the outside side sheets and throat sheet and back head for a distance of from 12 to 20 in. upward from the firebox ring.

Flexible Staybolt and Radial Stay Sleeves and Caps.—Flexible staybolt and radial stay sleeves are welded to the outside firebox sheets, including the roof sheet and combustion chamber shell course. Threaded sleeves were previously standard practice, before welding was adopted but as they necessarily had very few full threads in the sheet they were subject to leakage. Various types of sleeves are shown in Fig. 7.

Stoker Inlet.—Some stokers discharge coal into the firebox through sleeves in the form of large tubes which extend through the back head and door sheet. The edges of the sleeves are beaded and welded to the door sheet and back head in a manner similar to that described under Tubes and Flues.

Non-Pressure Parts.—Welding is used extensively to form joints in non-pressure parts such as shrouding, steam dome and sand box casings, ash pans and smoke boxes, but as these present no problems the practices are not discussed in detail.

Locomotive Cylinders

One of the recent and interesting developments involving applications of machine oxygen cutting and arc welding to locomotive construction is the production of all-welded locomotive cylinders

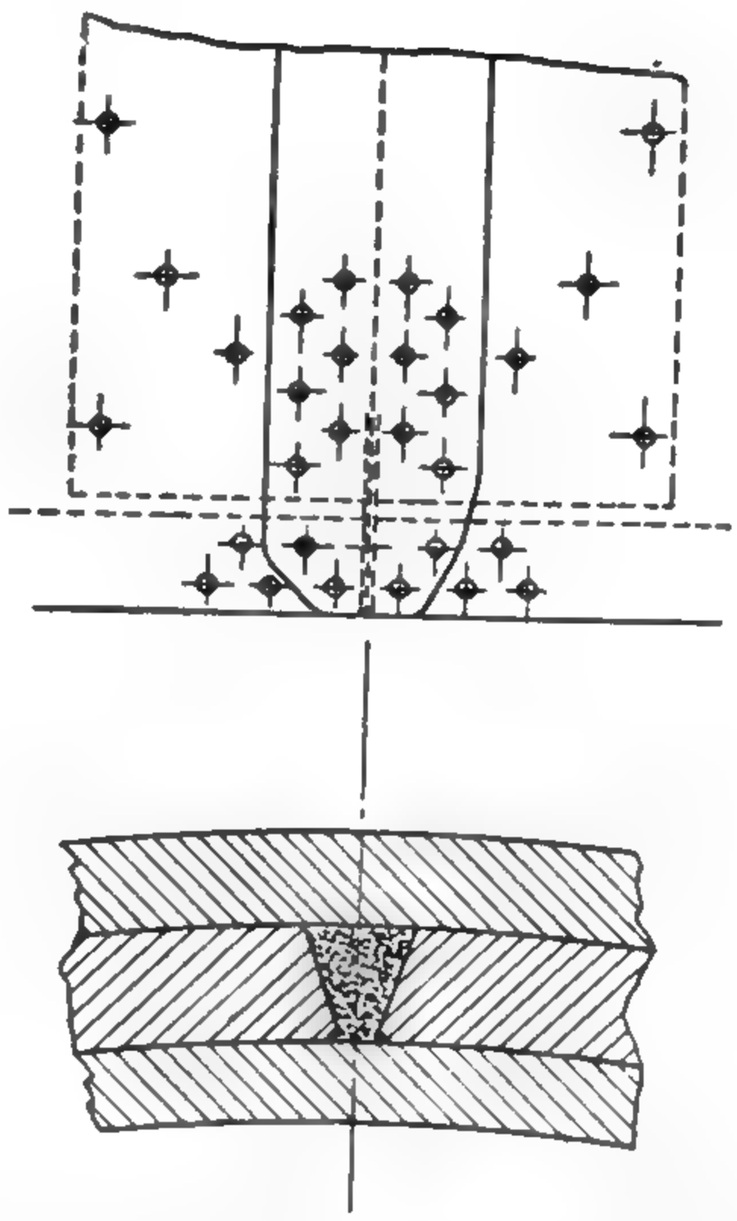


Fig. 6.—Seal Welding at End of Butt Straps

fabricated from steel plates. These cylinders, although 15% lighter than the cast cylinders they replace, are nevertheless stronger and lower in cost. Nearly two hundred and fifty of these welded cylinders have been put into service with highly satisfactory results. Details of the cylinders as manufactured by one railroad are given in the table below.

Composition of steel	AAR Specification M115-47, Flange Quality
Plate thickness, in.	1/2, 3/4, 1, 1 1/4 and 1 1/2
Lineal feet of oxygen cutting	1050
Weight of electrode required	1350 lb.
Weight of finished cylinder	13,600 lb.
Temperature of stress relieving	1050° F. for 5 hr.
Tested hydraulically at	500 lb.

Fig. 7.—Welded Staybolt and Radial Sleeves and Cap

Figures 8 and 9 show the parts required and the completed cylinders.

Air Reservoirs

Air reservoirs, which were originally made from sheet steel by riveting the longitudinal seams and attaching the heads by forge welding are now fabricated entirely by welding, submerged arc welding being especially favored and adapted to this type of work.

Locomotive Tender Construction

Tender Tanks.—Tanks are now fabricated by welding. The plate material is usually structural steel conforming to AAR Specification M116-45 or one of the various types of low-alloy, corrosion-resisting steels.

Tees or angles, employed as stiffeners for the relatively thin sheets and to attach swash plates, are generally welded with intermittent fillet welds although in some constructions continuous welds have been used. The location and arrangement of the tee or angle stiffeners have not been standardized and vary considerably with different designs. In some designs the tanks are all-welded and the swash plates are attached to the tee or angle stiffeners by riveting whereas in other instances all attachments are welded. The outside sheets are joined by continuous single-groove welded butt joints and the outside surfaces of the welds are ground to present a smooth surface.

Welded swash plates, braces and bulkheads are generally fabricated ready for attachment by welding in their proper positions in the tank to permit the major portion of the welding to be done in the open, thus leaving very little welding to be performed inside the tank after it becomes a partially closed structure.

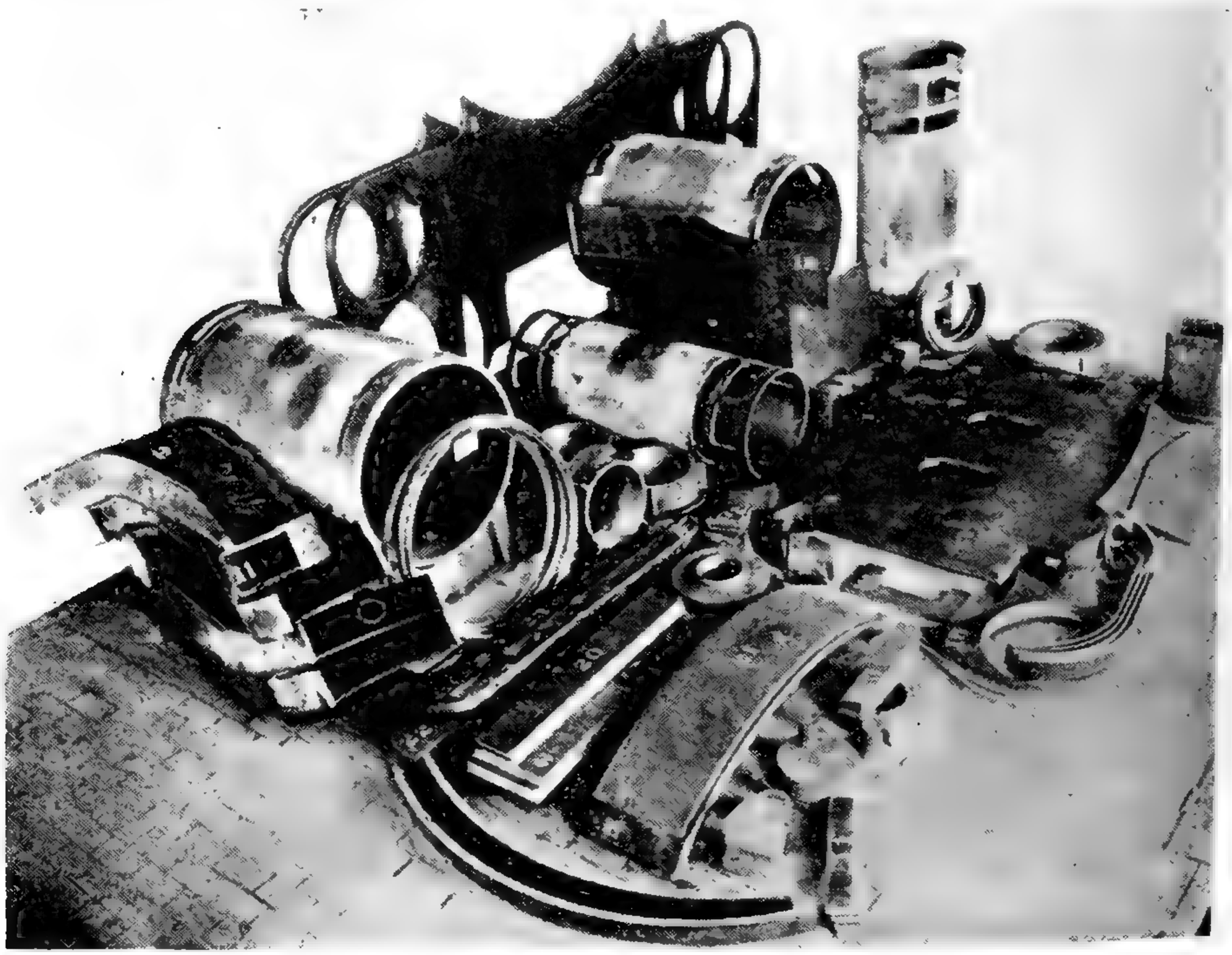


Fig. 8.—Parts for a Welded Locomotive Cylinder

These tanks are generally of the rectangular type though a number of semi-Vanderbilt, flat-top tanks have been completely fabricated by arc welding. When constructed for use with oil-burning locomotives some of the tenders have two separate compartments, one for water and one for fuel, while others have separate

fuel oil tanks that fit into the conventional coal space.

Welded tanks have been constructed with plate bottoms for mounting on the so-called *open-bottom* type tender frames which have floor boards upon which the tank rests. Others are built on cast-steel water-bottom tender frames which form the bottom of the tank and to which the tank plates are welded.

Welded tenders range in capacity up to 25,000 gal. of water and 30 tons of coal or 4000 gal. of oil.

Tender Frames and Tender Truck Frames.—A limited number of tender frames are made of structural steel shapes, such as H-beams, I-beams or channels with the necessary cross-bracing transoms, end bumpers, etc., which are arc-welded usually with fillet welds. Whenever possible this type of work is stress-relieved but good results in service are being obtained from assemblies which have not been stress relieved. In this work for best results it is important that the welding be done in the flat position.

In common with welded tender frames the number of tender truck frames that have been constructed by arc welding is limited. The welds are usually of the fillet type and the same procedure as that employed for tender frames has been found to give the best results. Some of these trucks are made of structural material with steel castings for the more complicated portions, partially welded and partially riveted.

Inspection and Testing

Inspection and testing of welds used in locomotive and tender construction does not involve X-ray examination with the exception of the all-welded boiler. Rail-

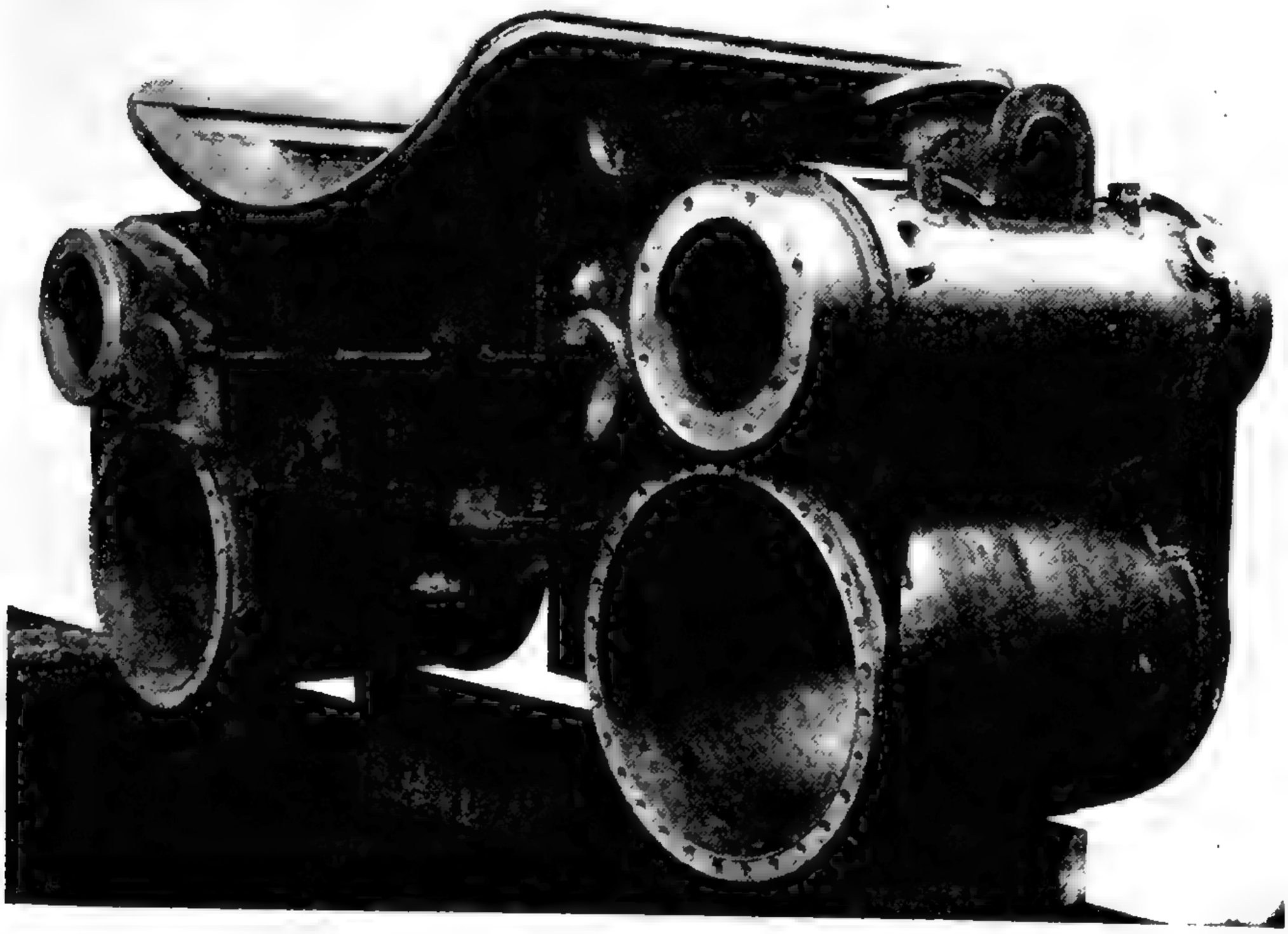


Fig. 9.—Welded Locomotive Cylinder

road welders are ordinarily qualified under the ASME code requirements described in Chapter 60 before being permitted to do welding on joints subjected to pressure.

The firebox welds are tested first when the boiler is given a hydrostatic test equal to 125% of working pressure and second when the boiler is given a fire test and the steam pressure is raised to 110% of working pressure.

Locomotive tender welds are tested for leaks by filling the tender with water.

The ICC code requires that air reservoirs be tested hydrostatically every

twelve months at 25% above the maximum allowed air pressure and that the entire surface be hammer tested at least once each eighteen months.

Maintenance

Codes.—A somewhat different condition with respect to codes exists in the applications of welding for the maintenance of locomotives and tenders than is the case in the fabrication of new equipment. Each common carrier is primarily responsible under the terms of the Federal Locomotive Inspection Law, which prohibits welding on only a few specific parts such as safety appliances, cracked driving rods, cracked wheel spokes, and welds inside the cabs. In general, the Federal Bureau of Locomotive Inspection controls welding practices under authority of the "condition and suitability for service" provisions contained in the law. In conformance with this responsibility, each major railroad issues its own instructions, sometimes in the form of a welding manual, to govern welding practices for the maintenance of any locomotive used on its line. Ordinarily neither radiographic inspection, stress relief, nor other special tests or treatments are made.

Materials and Processes.—Maintenance welding involves materials other than those mentioned under construction. Notable among the additional materials are cast and malleable iron, bronzes and aluminum alloys. Arc-welding with covered electrodes is in general use on steel parts although some railroads still use light-coated or bare electrodes for some work. Gas-welding equipment is used to some extent on steel, especially where arc-welding equipment is not available, and is, of course, essential for braze welding cast- and malleable-iron parts or cast iron with cast-iron welding rods.

Fireboxes.—The general details of firebox welding, when renewing the entire firebox, are essentially the same as for new construction and need not be repeated here. Completion of the welding on the firebox before inserting it in the back end of the boiler results in highest quality joints as the firebox can be turned to permit welding from the most advantageous position and all points can be welded from both the fire and water sides. In other instances the various sheets are prepared for single-vee groove welds, assembled in the back end, properly aligned, tack welded and then welded from the fire side. Where accessible, welding is also applied from the water side as in new construction. The welding conditions are arranged to facilitate making the water side of the weld clean and flush with the sheets with no gaps in which mud or sediment may collect.

Renewal of Sheets, Part Sheets and Application of Patches.—Firebox sheets are renewed in whole or in part, or patched, with sheets of firebox steel equal in thickness to the section removed. The joints are prepared and welded in the manner described in the foregoing paragraph. All welds are located midway between the two rows of stays and, where possible, welding is applied from both fire and water sides.

Pitting and grooving, due to corrosion, commonly occur in back flue sheets across the top knuckle and in the course of time develop into a crack. Repairs are made in some cases by cutting out the defective parts and inserting a butt-welded patch. In the best practice these patches are welded from both the fire and the water sides. Other defective parts of these sheets are cut out and new sections welded in place. In the application of small patches, the welding is sometimes applied from the fire side only to avoid the necessity of removing any considerable number of flues. Various types of repairs are also made to front flue sheets by cutting out portions containing defects and welding in new sections in a manner similar to that followed in the repair of back flue sheets, although the front flue sheets generally last much longer than the back ones.

Seal welding of superheater flues and boiler tubes follows the same practice as in new construction. The old tubes and flues that are removed may still be satisfactory for service except for the ends, which are destroyed when the tubes are removed, and some corrosion pits. If old tubes and flues are suitable for service, they are prepared for re-use by cutting off about one foot or less at each end and then lengthening the tube to the desired length by welding on a short piece of new tube. Corrosion pits are gas welded and the tube or flue applied in the same manner as a new one.

Cracks.—Cracks in firebox sheets not extending farther than the length of two staybolt pitches are grooved and welded

if the base metal is otherwise serviceable. Staybolts, if within the line of welding, are removed and replaced after completion of the welding. Some railroads apply patches to areas containing welded cracks at the first opportunity when the locomotives are out of service for repairs. Cracks in front and back flue sheets through the bridges between flue holes and elsewhere are grooved and welded. Cracks in firebox rings and complete breaks are also grooved and welded and new sections are welded in when required.

Patches.—Butt-welded patches are applied to surfaces supported by staybolts of normal spacing in the outside throat sheet, outside side sheets and back head. The bottom weld is located not lower than the bottom row of staybolts, or the patch extended to the bottom of the firebox ring and riveted thereto; the joints of all patches are located midway between two rows of staybolts. Welded joints in the back head inside of the cab or welded joints in the outside side sheets that extend inside of the cab are required to be covered with a riveted patch.

Tenders.—Repairs to welded tender tanks follow the same methods as used in original construction. Cracks in the sheets are grooved and welded if the condition of the base metal warrants, sheets and part sheets are renewed, cracked swash plates and the attachment welds for the plates and bracing are rewelded, and reinforcment in the forms of tees, angles or plates is applied to parts and in locations that show evidence of failure. Riveted tanks are repaired in a similar manner.

Repairs to welded tender frames and welded tender truck frames follow the same procedure as for new construction.

One-piece cast-steel tender frames, many of which are of the water-bottom type, one-piece cast-steel, tender truck frames and cast-steel truck side frames are very generally used by all railroads, and repairs to these members can best be effected by arc welding. The procedure followed in applying repairs to cast-steel tender and tender truck frames is similar to that for welding of new steel castings of comparable section. Repairs to cast-steel, truck side frames are made in conformance with Rule 23 of the Association of American Railroads *Code of Interchange Rules* governing the condition of and repairs to freight and passenger cars.

Locomotive Frames. — Repairing cracked or broken steel castings and restoring worn parts constitute an important part of the welding done on locomotives. One of the major steel castings frequently repaired is the locomotive frame. This may consist of the entire engine bed in some of the newer locomotives or of individual steel frames. Older locomotives have cast frames while some of the newer ones have frames which have been oxygen-cut from a rolled steel plate. (Wrought iron frames, once used extensively, have now been quite generally retired.) When the frame breaks, it is usually in an irregular pattern necessitating cutting out a large amount of metal with a torch in preparation for welding. Frames are comparatively rigid members and therefore do not yield readily as the large volume of weld metal shrinks. Unless precautions are taken to spread the members by means of jacks before beginning to weld, there is considerable probability that the shrinkage will cause either a break in the weld or a new break in the frame. Common practice is to allow about $^1/_8$ in. *expansion,* as it is termed, for shrinkage of the weld metal.

Broken frames have been repaired by thermit welding, brazing, bare metal-arc welding, and finally by the modern practice of shielded metal-arc welding. Both thermit welds and brazed joints are still in service.

Frame welds may be finished by grinding to provide a smooth transition from the welds to the base metal. In addition some railroads prefer to stress relieve the welds by heating them with charcoal, or other fuel, suspended in a basket around the joint, or by means of an oil torch.

Wheels.—Steel wheels break in the rim or spokes and ICC regulations require that if three adjacent spokes or 25% of all the spokes in a wheel are broken, the locomotive must be withheld from service until repairs are made. Broken rims are repaired in the usual manner by cutting out the crack with a torch and welding with covered electrodes. The tire must, of course, be removed while this is being done. In the case of broken spokes, especially the short ones, it is necessary to spread the joint with jacks after the crack has been cut out from both sides. Unless this precaution is taken the weld may crack in cooling.

Many other parts such as steel cylinders, roller bearing housings, guide yokes, shoes, wedges and binders are repaired by welding.

Braze-Welding of Castings.—In recent years the practice of building up the wearing faces, such as the hub face and the shoe and wedge faces of cast-steel driving boxes with a bronze welding rod, usually a leaded bronze, has been widely adopted. Crown brasses and other large bronze bearings are similarly reclaimed. The usual practice is to apply the bronze welding rod by either metal-arc or carbon-arc welding, using electrodes one-half inch or larger in diameter.

Welding Cast Iron Parts.—Most cast-iron parts that become cracked or broken are repaired by braze-welding only a few being welded with cast iron. Some arc welding has been used with special electrodes but the results have not been uniformly successful. One of the largest parts commonly repaired is a cylinder. Breaks in the cylinder barrel or valve chamber are the easiest to repair. If the cracks extend into the internal stiffening ribs it is difficult, if not impossible, to gain access to them for chipping. In such cases the cylinders should be scrapped as the external welds will not last indefinitely when cracks are present in the internal bracing bar. It is practical in some cases to remove a section of the external wall to give access to an interior wall for braze-welding.

Cylinders must be preheated to about 700° F. before braze-welding and to a still higher temperature if the welding is to be done with cast-iron rods. This is accomplished by enclosing the cylinder in a temporary furnace constructed of fire brick with loose bricks or openings to permit manipulation of the torch. When the braze-welding or welding is completed the fuel bed is renewed and the fire allowed to burn out undisturbed so that the entire cylinder will cool slowly to shop temperature.

One of the most important details in repairing a broken cylinder is proper preparation of the crack. It is opened up by means of a chipping gun to at least $^1/_8$-in. wide at the bottom. Holes may be drilled at the ends of the crack, preferably located by magnetic particle inspection, to prevent further spreading. The surfaces to be welded should be sand blasted to remove any graphite, oil or other contaminants.

Cast-Iron Wheel Centers.—Some of the older locomotives are equipped with cast-iron wheel centers on which the steel tires are mounted. It is necessary to repair broken spokes in these wheels just as in the case of steel wheels (rim breaks are not necessarily repaired). The lack of ductility in cast iron is compensated for by making a cut in the rim of the wheel to allow some movement during cooling after the braze-welding has been finished.

Back Heads.—Steam leaks around the back head of a locomotive cylinder are objectionable in the winter because they obscure the vision of the engine men. Bolted heads are difficult to maintain leak-proof, so some railroads have resorted to braze-welding these heads to the cylinder. A U groove is machined in the steel head and four studs are used to hold it in place while braze-welding is accomplished. Preheating the cylinder is essential and sand blasting of the joint before welding desirable. A properly braze-welded head remains tight during the serviceable life of the cylinder.

Numerous other iron castings on a locomotive, air pumps for example, are repaired using the same fundamental procedure outlined above. One exception to the above procedure is the application of brass to locomotive pistons, in this case to restore worn off metal instead of repairing a fracture. The metal is usually applied only to the bottom half of the piston. Preheating is common practice as is also the use of flux-coated, manganese bronze rods.

Chapter 28 should be consulted for further information on the welding of cast iron.

Welding on Medium and High Carbon Steels

Very little welding is done on medium or high carbon steels, whether they are plain carbon or alloy. These steels are used for critical forgings such as axles, motion work, rods, pins, wheels and tires. Welding of cracked rods is not permitted under the ICC rules but restoring worn metal on the ends of side and main rods is permitted and practiced to some extent under properly controlled conditions. Welding worn flanges of wheels and tires is not approved.

Welding on Low-Carbon Steel Parts

There are practically no restrictions covering the welding of parts made of low-carbon steel whether they are forgings, pressings or other fabrications. Welding is used to repair cracked or damaged parts, restore worn metal and fabricate new parts. Such items as brackets, equalizers, hangers, transoms and supports of various types are some of the numerous items in this class. Hard surfacing may be applied at the wearing zones to lengthen the life of the part. See Chapter 21 on Surfacing for further details.

Diesel Electric Locomotives

The Diesel locomotive is constructed in a similar fashion to other units used on the railroads such as the freight and passenger cars. The unit is made up of an underframe, side frames, nose end, rear end and roof section.

Design.—Design of these various components is based on the use of mill sections such as I-beams, channels, angles, and bars. Some forgings and castings are also used. The joining of these members into a finished product is done by means of various welding techniques.

The acceptance of this type of motive power by the railroads has created sufficient manufacturing volume to permit certain principles conducive to high production, high quality weldments. These principles include the use of subassemblies, control of fit-up and welding sequence, and the extensive use of positioned welding.

Subassemblies.—The breakdown of the car body into subassemblies allows the employment of jigs and fixtures to permit the assembly of the detail parts accurately. It further allows their fabrication in a flat position so that AWS-ASTM E-6020, E-6030, E-7020 and E-7030 electrodes may be used to permit high welding speeds. The regularity of

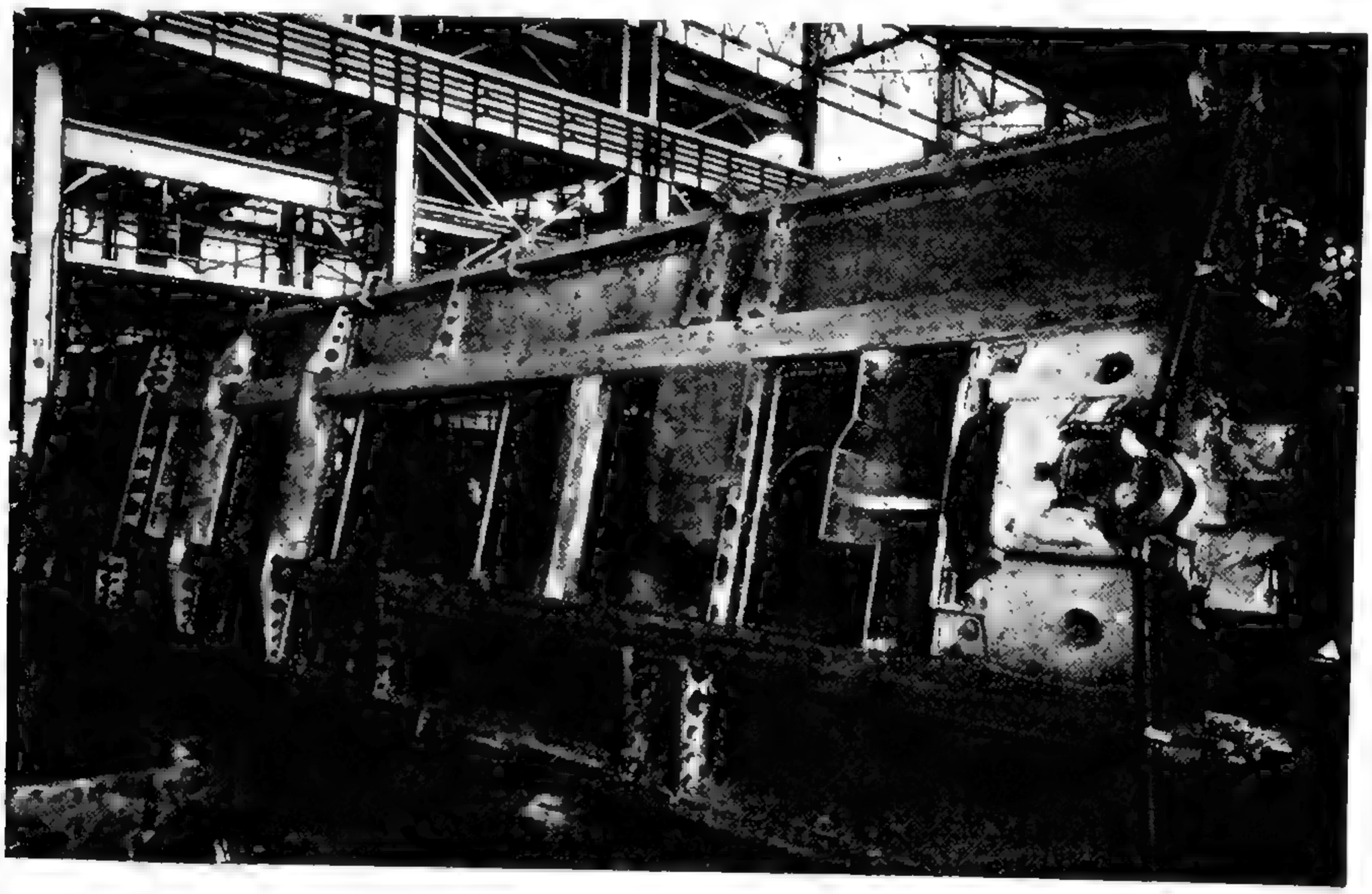


Fig. 10.—Underframe of Diesel-Electric Locomotive

Inspection and Testing

Very little in the way of inspection or testing is done on welds made in maintenance work. Firebox and flue welds may be tested hydrostatically following extensive firebox renewal work. Welds in tender side walls are tested by filling the tank with water. Soundness of welds may be checked while machining a part. Other than the above, the quality of a weld is determined by the serviceability of the welded part. Magnetic particle inspection equipment is available in many shops and may be used in inspecting welds or locating cracks in preparation for welding. (See Chapter 42.)

procedure and sequence in welding jigged subassemblies results in accurate weldments with proper states of residual stress so that the final assembly is readily welded without excessive cutting and fitting. Due to the relatively small size of the unit subassemblies, the important ones may be easily stress relieved to reduce stresses to a known level and stabilize them for accurate machining when this is necessary. Figure 10 shows the underside of an underframe illustrating the heavy beam construction of the center sills to which are joined various wrought cross members and plates. Manual metal-arc and submerged arc welding are used in this fabrication. Low-alloy, high-strength steel is used for the more highly stressed portions and plain carbon steel of specified chemical and mechanical properties for the balance of the structure.

Crankcase.—The size of the crankcase for a long life Diesel engine as required in railroad service is such that it is very difficult to make as a casting. This vital part is therefore made by welding together wrought members such as plates and forgings of carbon or alloy steel with properties suitable for the stress level of the part. Prior to machining the complete assembly is stress relieved in a circulating-air type furnace with automatic zone control. The same welding principles as apply to the car body structure are used in the manufacture of the crankcase. Subassemblies, downhand positioning and the use of jigs and fixtures insure a high quality, dimensionally accurate product.

The welding of crankcase end and cover plates in the downhand position is accomplished by positioners as shown in Fig. 11.

Miscellaneous.—Due to the heavy sections joined and the continuous nature of the joints, extensive use is made of submerged arc welding. The underframes, parts of the superstructure and the crankcase are partially welded by this process.

Figure 12 illustrates the side frame jig which allows the use of downhand electrodes for welding these important members which are used as stress-carrying members in a diesel-electric locomotive.

Spot welding is used to join sheet metal parts up to $^{3}/_{8}$ in. thick and electronically-controlled equipment is used on the highly stressed applications.

Miscellaneous other welding processes are used in Diesel-electric locomotive manufacture. Stud welding, torch and resistance brazing using silver alloys and soft soldering are practiced extensively in production.

Mention of the equipment and processes used in joining the parts of the locomotive is only a partial story. Adequate supervision, proper welding procedures, and an independent inspection organization are fundamental adjuncts to attain high quality and production levels.

RAILROAD PASSENGER CARS

Materials

Low-Alloy High-Tensile Construction.—In 1912, shortly after the advent of the all-steel passenger car, the Post Office Department issued a specification for the construction of railway mail cars.

This specification deals with the loads to be resisted, allowable stresses, minimum section moduli of various members, and other significant details vital in case of collision.

In 1939 the Association of American Railroads issued a similar specification, but more thoroughly specifying the strength requirements at various locations in the car, including certain stiffness requirements.

The demand for light-weight passenger cars has encouraged the development of the low-alloy high-tensile steels. These steels with a yield point of 50,000 psi. are being used extensively in the passenger cars being built today. Low-alloy steels can be welded by all of the welding processes; therefore, their acceptance has been quite general.

Design

Underframe.—The underframe of a railroad passenger car (Fig. 13) consists of the center sill, side sills, cross bearers, floor beams, draft sills and body end sills. Considerable manual arc welding and automatic submerged arc welding are used to join the various members of this subassembly.

As Fig. 13 shows, the center sill is the longitudinal member in the center of the car. This member is designed to carry the buffing load of the car from one end to the other. It is required to carry a load of 800,000 lb. in compression. The center sill is made by welding together two Z-sections. The top

flanges are joined together so that the unit forms a flanged U-section. The weld joins the $^{3}/_{8}$-in. thick flanges in a butt joint 60 ft. long.

The parts are clamped together by hydraulic cylinders which exert pressure horizontally and also downward. The fixture has a longitudinal camber of $4^{1}/_{2}$ in. to compensate for the shrinkage of the 60 ft. weld. When removed from the jig, the sills are perfectly straight.

Side Sills and Bolsters.—Side sills are the two longitudinal side members running the full length of the underframe.

Cross bearer and floor beams are the transverse members that support the floor load and transmit it into the side sill. These members are pressed channels and rolled Z-sections and are manually arc-welded to the center sill and side sills.

Located near each end of the underframe are two large transverse members called bolsters. These are fabricated by welding two vertical webs, spaced apart, to top and bottom cover plates in order to form a box section. The welding is done with an automatic submerged arc-welding head mounted on a portable gantry frame.

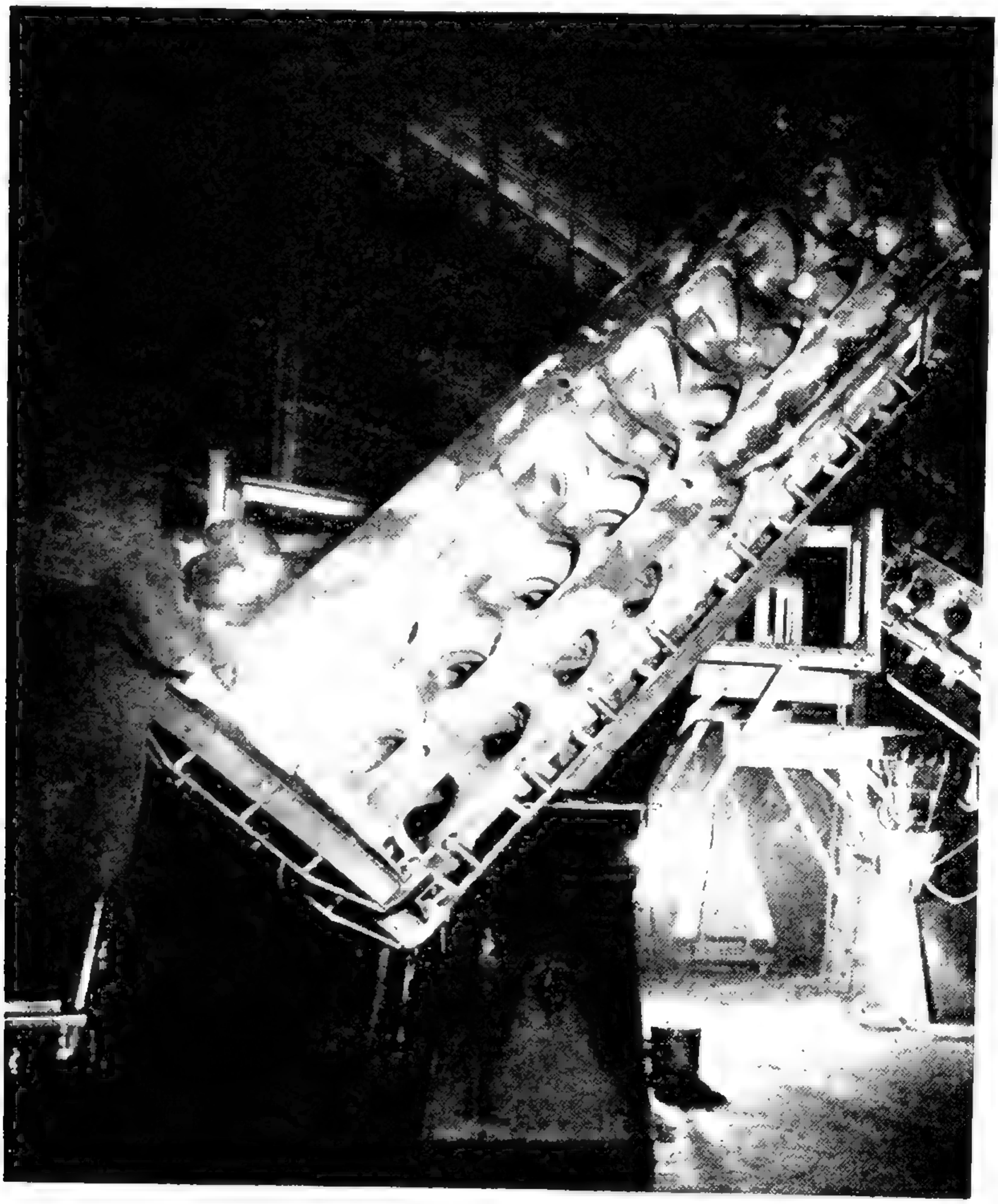


Fig. 11.—Diesel Locomotive Crankcase on a Positioner

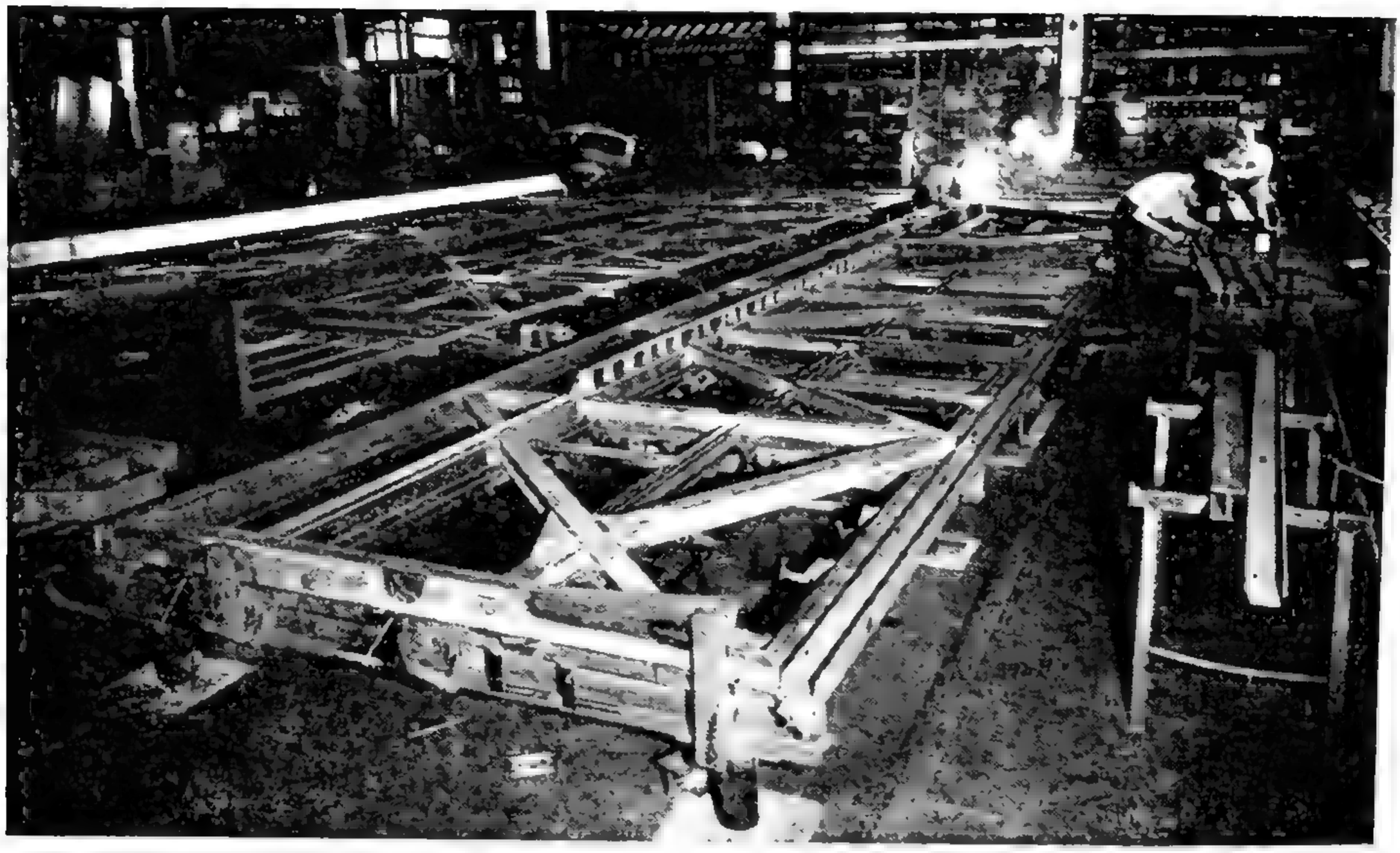


Fig. 12.—Jig for Side Frame of Diesel Locomotive

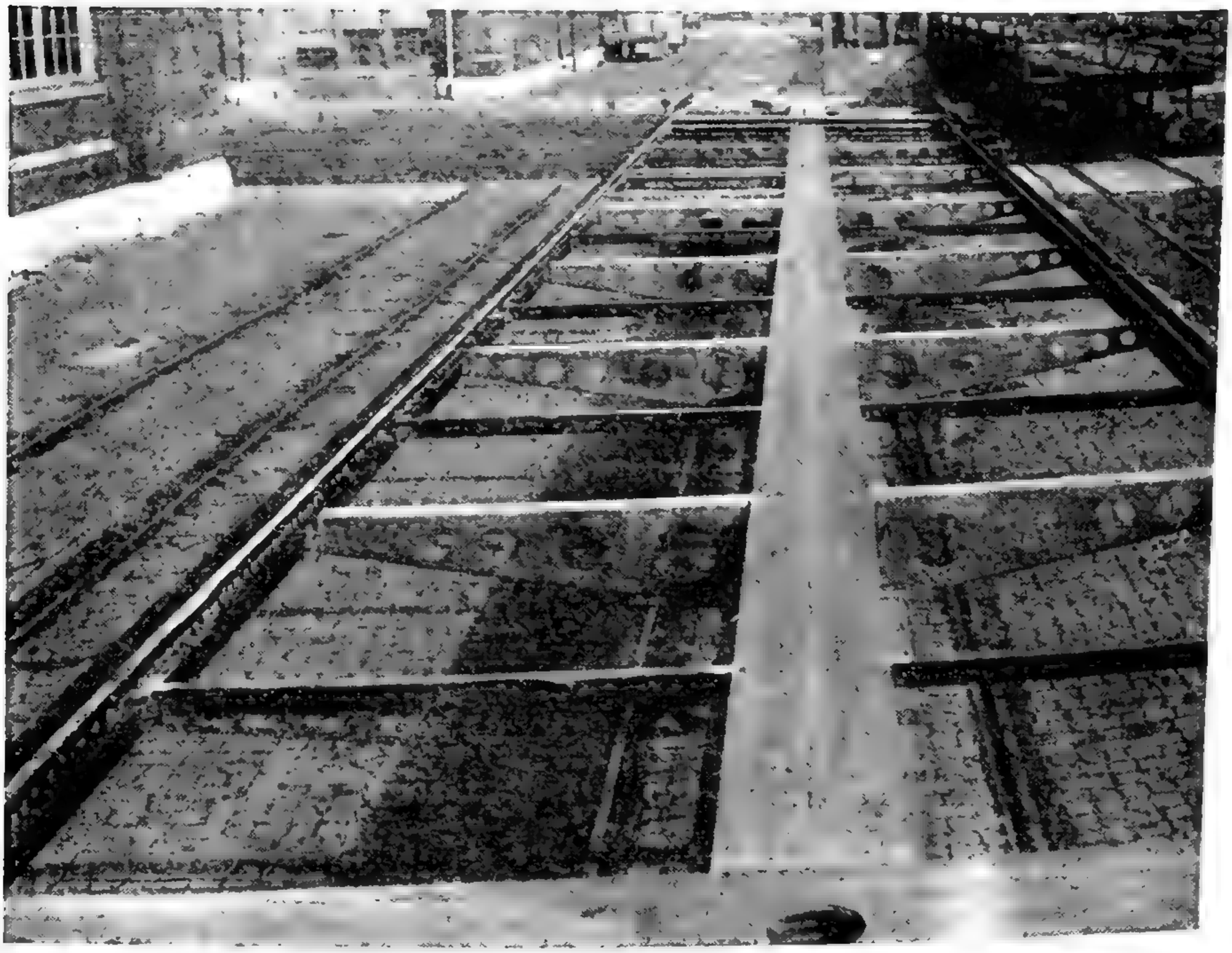


Fig. 13.—Underframe of a Passenger Car

Car Body

Side Subassemblies.—Sides for a passenger car are divided into two main subassemblies, the framing and the side sheet. Both these units are built in complete car-sized assemblies, before they are joined together. There is a very definite reason for this. The side has flat panels, and every operation must be performed in a manner that will not produce any buckles in the side sheets. The framing is arc-welded together. By keeping the two operations separate, the shrinkage from arc welding takes place without affecting the side sheets. The framing is straightened before the side sheets are spot welded to it, thereby producing a flat side with no distortion.

The side sheet of a car side is divided into approximately sixteen sections by a horizontal seam, running the full length of the side midway between top and bottom, and seven vertical seams. Building of a side begins in the steel mill, where the individual sheets are inspected for flatness with close tolerances to insure a flat car side.

The first manufacturing operation is to shear the sheets to size and cope out window openings. Next corrugated stiffeners are spot welded to the side sheets to prevent them from buckling. The attachment of stiffeners to the side sheets is an important development in producing flat sides. The entire area of the side (except clearances for the attachment of framing members) is covered with corrugated stiffeners, which prevent any distortion or buckling of the side sheet.

After the corrugated stiffeners have been welded to the side sheets, the next operation is to join these sections together to form one large sheet that extends the full height and length of the car side. Joining of the side sheet sections is an interesting application of submerged arc welding. The side sheets are of 14 gage (0.075 in.) thickness, and the joint is a square-groove welded butt joint. First the horizontal seam is welded, and then these units are joined together by vertical seams. The track for the welding head carriage is mounted upon a stationary fixture, and the sheets are moved underneath this fixture from seam to seam. The table top is covered with rollers so that the sheets move freely.

Side Framing.—The side framing is made from arc-welded Z-sections. The horizontal members are full length, but the vertical members or posts are split into three pieces in order to keep the number of different lengths that will be required to a minimum.

Figure 14 shows side framing members being welded together in a side frame jig. The members are held against locating stops by specially designed clamps. All clamping parts of this side frame jig are attached to the vertical members so that they can be moved when it is necessary to reset the jig for a different car plan with changed post spacing.

Railroad car sides are built with a camber, which must be provided by the side frame jig. Hence it is necessary, as the vertical members of the jig are moved to different locations, to adjust them in height to fit the camber curve. This is accomplished automatically by supporting the top part of the vertical members on a roller. The roller runs along a track that is set for the proper camber, and the jig parts raise or lower with the track as required by the camber curve. When clamped at the desired location, they are automatically at the correct camber.

After the side framing has been removed from the welding jig, it is taken to a straightening position, where all the flanges to which the side sheet will be spot welded are checked for perfect alignment.

Side Framing to Side Sheet.—Figure 15 shows the side sheet in place against the copper backing of the side spot-welding fixture. This $^1/_2$ in. copper backing supports the entire car side and permits welding pressure to be applied to any point desired over an area $8^1/_2$ ft. high by 85 ft. long. In the illustration, the side framing is being lowered for assembly against the side sheet.

Spot welding of the side framing to the side sheet is performed on a vertical jig for several reasons, the most important of which are:

1. Distance is a minimum from the eyes of the operator to all parts of the work.
2. Shop dust and dirt are prevented from settling on the copper backing plate.
3. The cooling water runs off freely.
4. The side is in its natural position.
5. Less floor space is occupied in the shop.

Fig. 14.—Welding Side Framing Members of a Passenger Car

Fig. 15.—Side Sheet Against Copper Backing Ready for Side Framing to Be Put in Place

Automatic Indexing.—The automatic side welding machine, Fig. 16, has two welding electrodes that make a series weld. These electrodes, along with the transformer unit and air cylinders, are indexed automatically in either a horizontal or vertical direction as desired. Indexing is accomplished by means of a specially designed motor which is started and stopped for each index. The length of time that the motor runs is governed by an electronic sequence panel, and spacing of the welds is controlled by adjusting a timing panel. A special type of relay gives quick braking for the motor and accurate spacing. The operator has available on his comprehensive control panel all the necessary dials and instruments to adjust welds and indexing.

A different type of traveling spot welding machine is shown in Fig. 17; it is used for making freight car sides as well as sides for passenger cars. The car sides are mounted on a sloping backing jig and the machine moves along a rail parallel to it. The welding carriage, complete with transformers and guns, moves in a vertical direction paralleling the slope of the jig. The electrical connections are so arranged that it is possible to make rows of either series or single spot welds vertically and horizontally. After the initial spot (or two when in series) the controls can be set for automatic indexing.

Roofs.—Roofs for the railroad passenger cars are seam-welded by the machine and jig shown in Fig. 18. This machine has roller electrodes mounted on a carriage traversing the entire width of the roof. The track for the transverse movement is shaped to conform with roof curvature so that welding pressure in all positions is normal to the roof. Two circular electrodes are used side by side, connected in series so as to weld seams simultaneously, one on each of the two sheets that butt together on the roof car line. The roof car line is supported by a copper backing bar, which in turn is supported by a steel structure capable of withstanding the pressure of the two welding wheels.

A complete roof is fitted up at one time. The car lines or transverse supporting

Fig. 16.—Automatic Spot Welding Machine for Car Sides

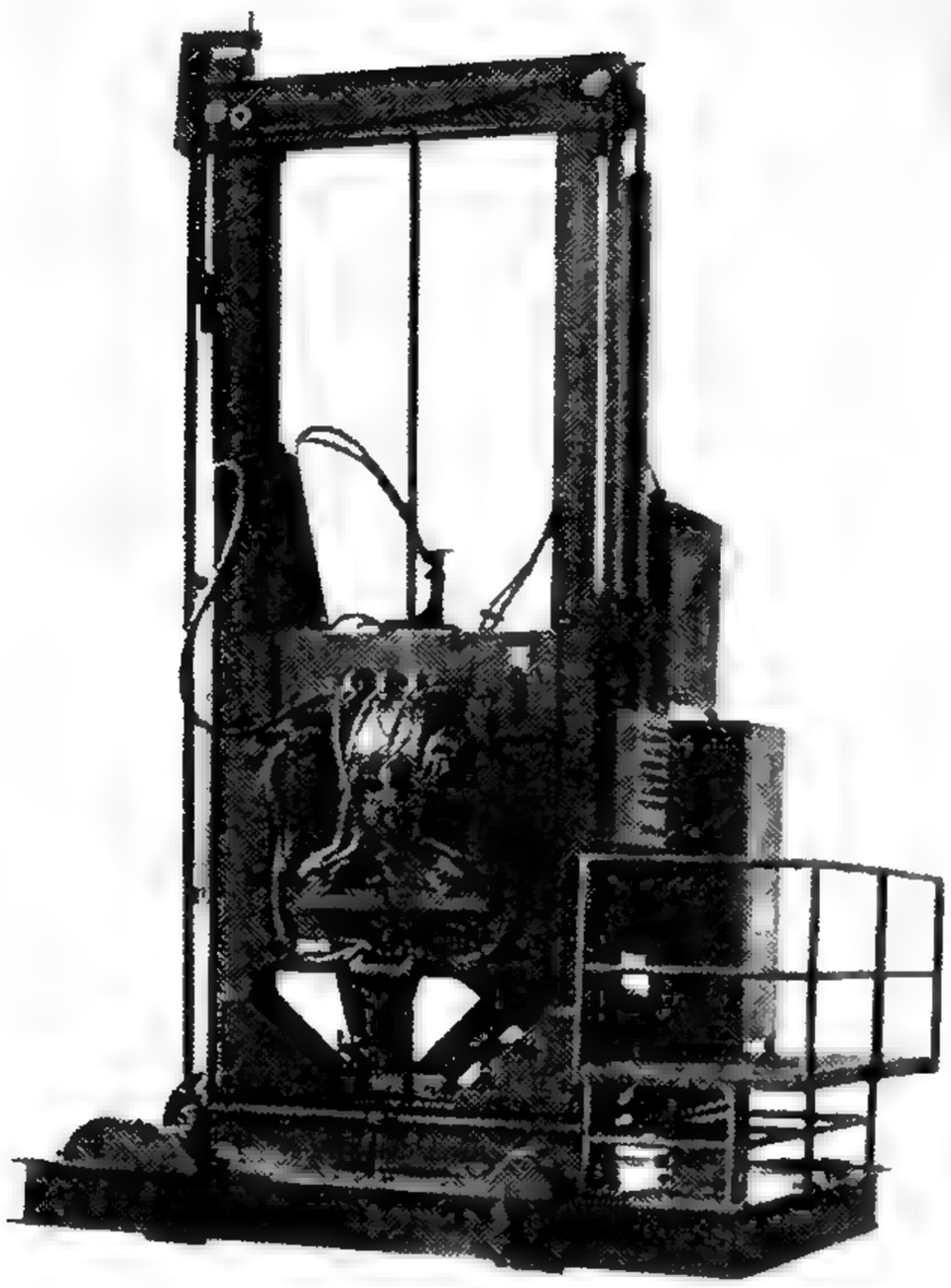


Fig. 17.—Series Type Spot Welding Machine for Fabricating Car Sides

members of the roof are fitted over the copper backing supports. The electrode wheels roll from one end of the car line to the other, welding the sheets to the car-line. The sheets, as shown in Fig. 18, are laid transversely across the roof and are strapped firmly into position to insure that the correct contour is maintained during the welding operation. After each seam is welded the machine is moved longitudinally to the next seam.

Ends.—Ends for the passenger car, while simple in construction, require the use of several different welding processes. Spot welding is used to attach stiffeners to the end sheets. The anti-telescoping plate is mainly of spot-welded construction. Diaphragm and posts, which are part of the end structure, are strength members specially designed for collision requirements Oxygen cutting is used to trim the ends to the desired shape. A reinforcing doubler plate is submerged arc welded to the web of the I-beam post with the equipment suspended on the gantry frame described in the discussion on underframe parts. Shielded metal-arc welding is used to join the ends of stiffeners to sills, ceiling plates, etc.

Stainless Steel Construction.—The strength requirements for passenger cars are detailed in the previous section covering cars constructed of low-alloy high-tensile steel.

Materials.—The material used in the construction of stainless steel railway cars is unstabilized 18–8, austenitic stainless steel. This material cannot be hardened by heat treatment but gains its strength from cold working.

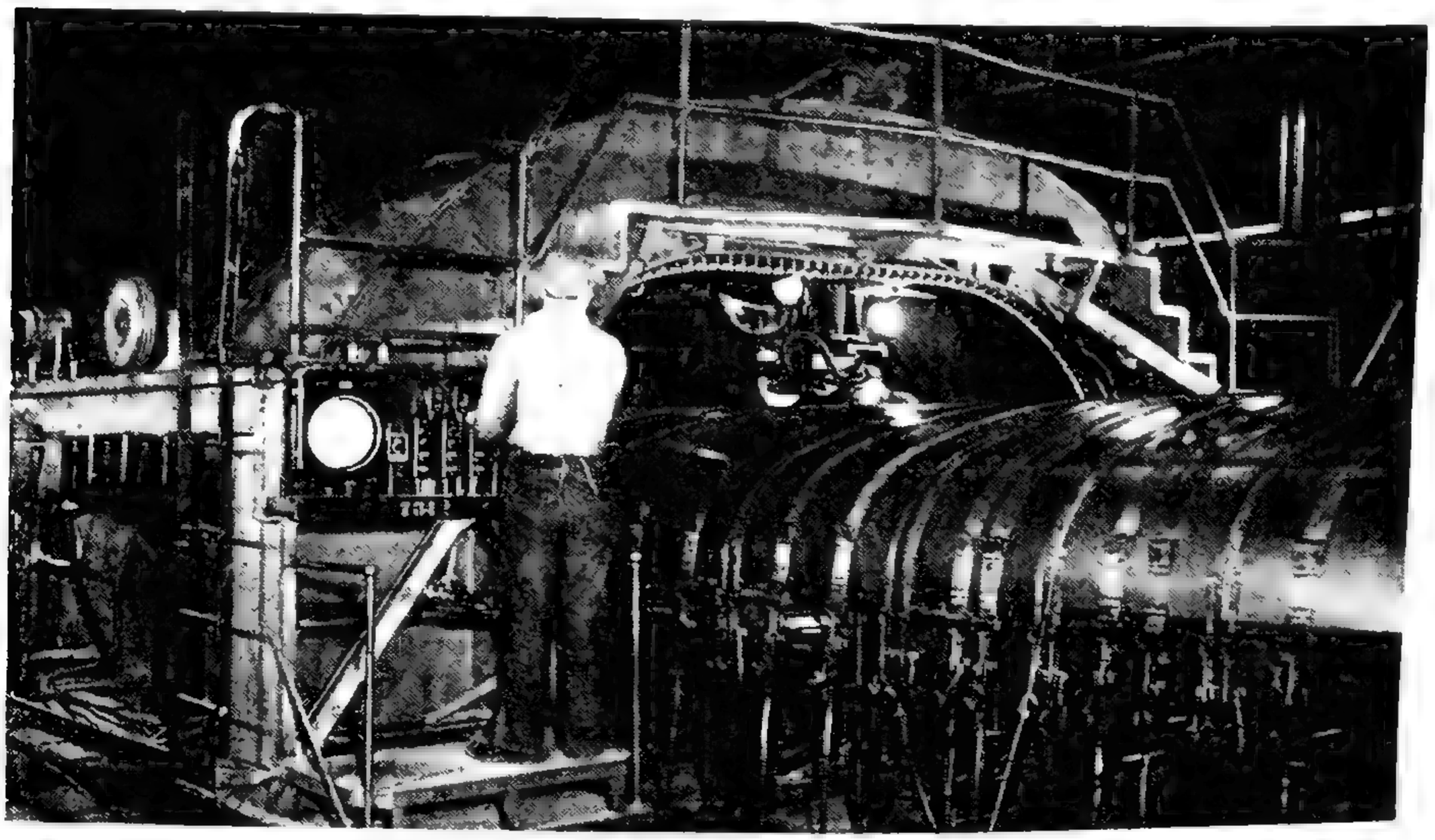
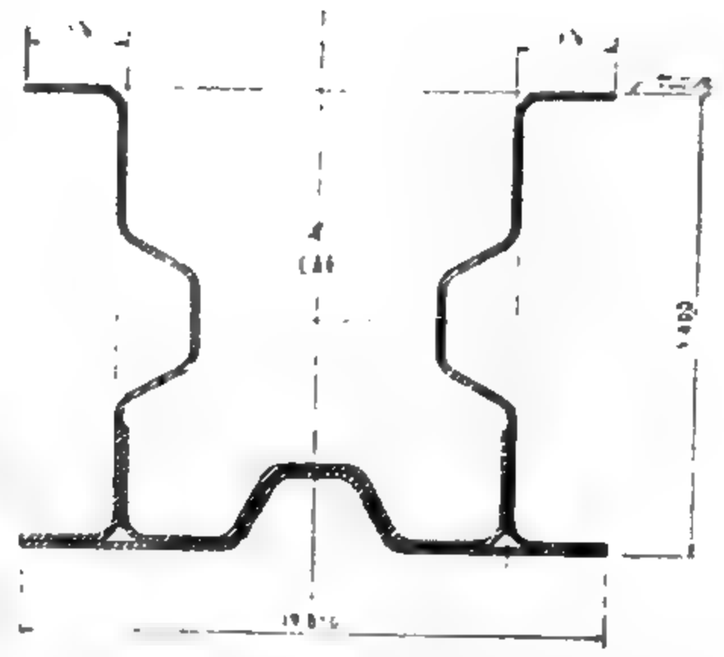
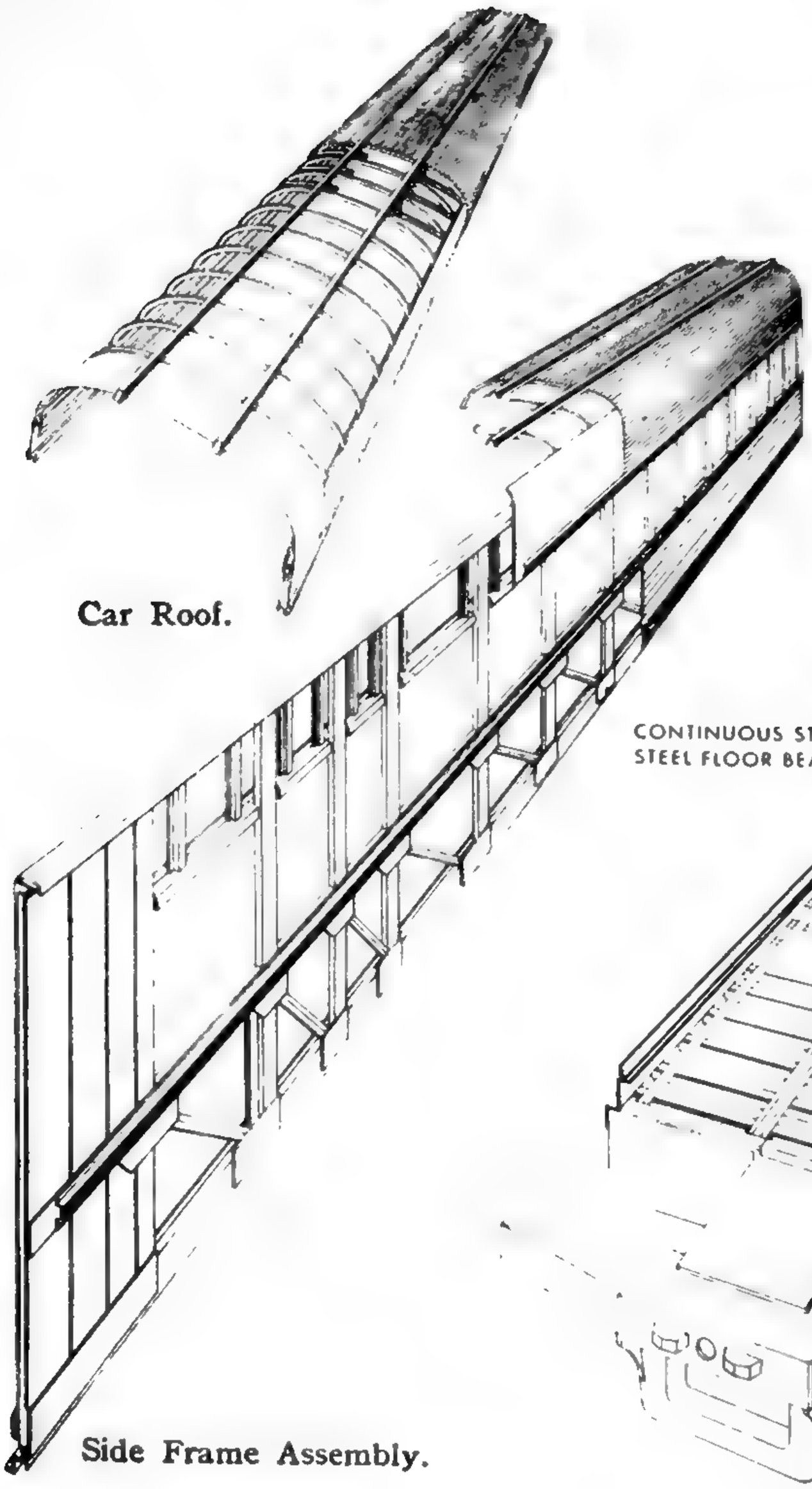


Fig. 18.—Jig and Seam Welding Machine for Car Roofs

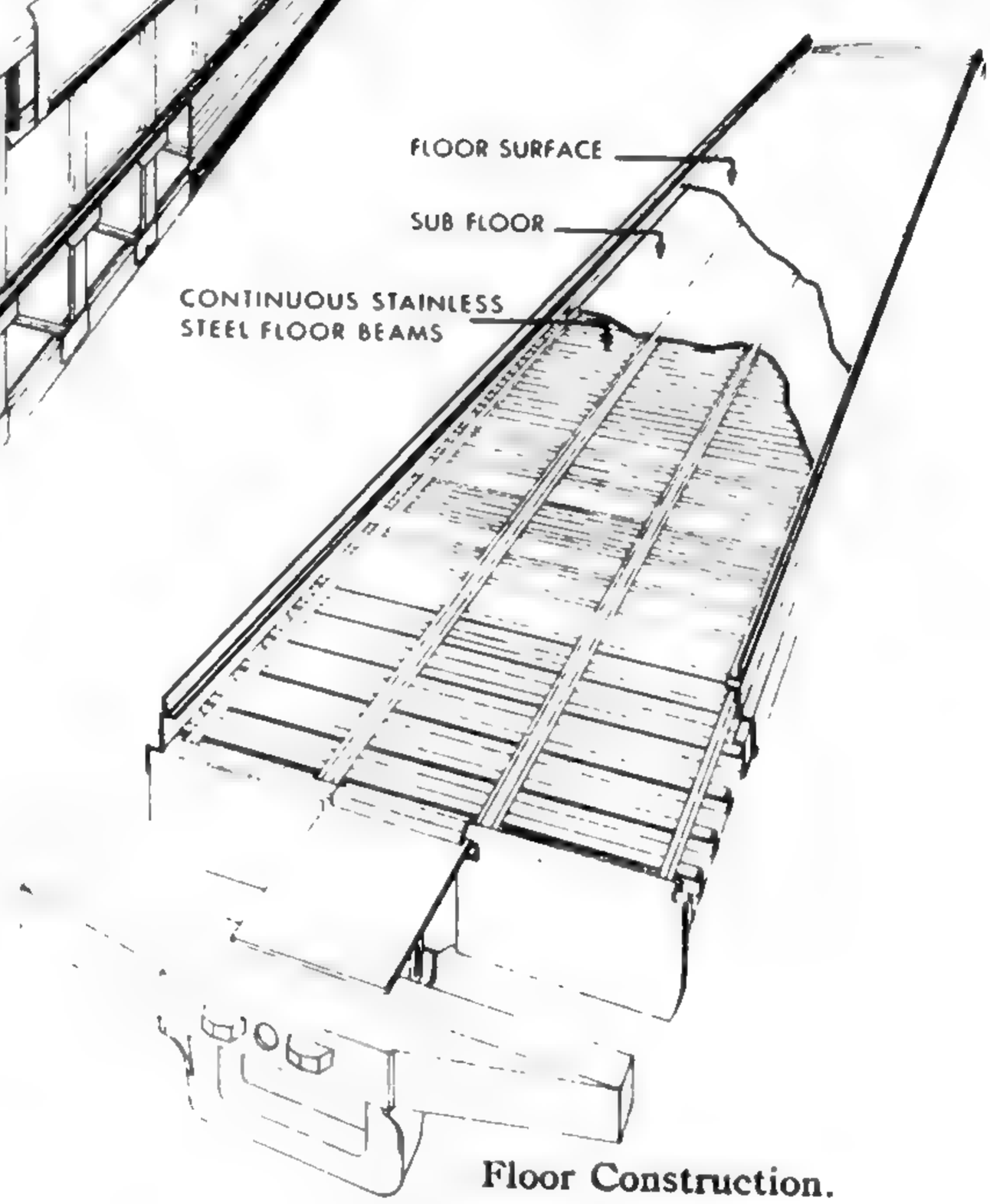


Center Sill Cross Section.



Car Roof.

Side Frame Assembly.



Floor Construction.

Fig. 19.—Details of Construction of Stainless Steel Passenger Car Body

Information on the mechanical properties, corrosion resistance, workability and weldability of the stainless steels will be found in Chapter 31A.

The most desirable method of joining stainless steel is by resistance welding with short current time duration which reduces carbide precipitation and annealing to a minimum and produces welds of high ductility. The electrical resistance is six times that of low-carbon steel and the bright scale-free surface which never requires cleaning other than wiping off dirt and grease makes this an ideal material for resistance welding.

Design and Assembly of Stainless Steel Railway Car Structures.

The following sections describe briefly the principal components of the car structure shown in Fig. 19.

Car Floor Assembly.—The floor assembly consists of an end underframe assembly of the arc-welded, low-carbon alloy steel which is riveted to a center sill made of stainless steel drawbench sections resistance welded together. The transverse stainless steel floor beams and pans are resistance welded to the center sill and side sill members in a floor assembly jig. The side sills enclose the

floor beams and the end underframes. After the car floor is assembled it is inverted and the underfloor equipment installed before it is sent to the final car-assembly station.

Car Side Assembly.—The side frame is a truss-type structure with shear panels at the ends and is constructed with $1^1/_4$ in. camber. The completely resistance welded sides in conjunction with the roof and floor, support the fully equipped car at the proper camber. The side frame is resistance welded to the floor side sills, the end frame and the roof.

After the car is assembled, fluted panels are attached over the truss structure and *dead light* panels are installed between window frames to provide external trim.

Car End Assembly.—The end frame assembly consists of an end sheet, angles for connections to roof and side frames, and collision post assemblies which tie between the end underframe and roof purlins. This assembly is entirely resistance welded stainless steel.

Car Roof Assembly.—Z-shaped roof car lines, hat-shaped roof purlins and side plate assemblies are assembled in a cambered jig. Corrugated assemblies 80 ft. long are laid over this frame. The entire structure is stainless steel, spot-welded. The completed roof structure is lifted out of the assembly jig and inverted. Piping and wiring, air ducts, air conditioning equipment and ceiling supports are installed before the roof is sent to the final car assembly station.

Final Assembly and Trim.—The finished car floor, sides, ends and roof are assembled by spot welding, forming an all-welded stainless steel car structure (Fig. 20). To this structure is added stainless-steel external trim and aluminum, carbon steel and stainless steel internal trim. Shielded metal-arc welding is used in limited applications on carbon steel and stainless steel for assembling parts other than primary structures. Inert-gas metal-arc welding is used extensively on aluminum trim parts. Cabin and bedroom assemblies are made almost entirely of spot-welded aluminum sheet.

Details of Construction and Erection

Jigs and Fixtures.—Welding jigs are designed to hold two or more parts in position with sufficient clearance for welding tools. Parts are always jigged from flanges, never from edges or bend radii. Therefore, for correct jigging it is necessary to have correct parts.

To allow use of unskilled labor, jigs are built with ample mass. Portable jigs are limited to those weighing 15 lb. including parts and, therefore, most jigs are fixed. For maximum production, jigs should be used only for tack welding or while key spot welds are applied and the welding completed after removal from the jig while the jig is being reloaded.

Large jigs may include structures for supporting welding guns and cranes. Small jigs, for low production, may use plywood with reinforced edges, cutouts

Fig. 20.—Completed Stainless Steel Car

and angle iron clips. Masonite may be substituted for tank plate conforming to AAR Specifications M116-45 on jigs with limited life. Portable jigs, used with pedestal welding machines, should be made of nonmagnetic materials.

Where shrinkage or distortion due to welding is involved and cannot be eliminated by procedure or sequence, counter jigging can sometimes be used to produce a finished part of the correct dimensions after welding. The major problem in this method is to determine the welding which must be done in the jig to hold necessary dimensions and yet not produce distortion which would make removal of parts from the jig difficult.

Portable resistance welding installations, as shown in Fig. 21, are desirable for reasons of flexibility of equipment and immobility of parts to be welded. Special-purpose, automatic welding machines (Fig. 22) can be justified when the number of welds is such that the speed of welding can produce a labor and floor-space saving sufficient to justify the investment.

Fig. 21.—Welding Stainless Steel Car Side to Floor Connection with Portable Spot Welding Machines

Resistance Weld Testing and Inspection.—Before welding begins on a job the spot weld setup is tested on test coupons made under production conditions. On light metal, penetration is checked by the peel test and on heavier metal the etch test is used. On all metals, tension-shear tests are made to check the shear strength of the weld. This shear strength must be above an established minimum value. The test weld is recorded by an Ampere-Squared-Second Recorder and all welds made on the job can be compared to the test weld. After resistance welds are made they are examined for appearance and con-

formity, in quantity and location, to engineering drawings and the Weld-Recorder record is examined for indications of irregularity of power input to each weld.

Repairs to Passenger Cars

The advent of the all-welded type of car has naturally led to the adoption of either arc or spot welding for repairs. Maximum economy and minimum delay in restoring cars to service results if repairs can be made without removing the part from the car. This may lead to a combination of welding and riveting on some of the older cars, but this is not objectionable.

Corrosion or mechanical damage to body and end sheets necessitates renewals in whole or in part. It may be more economical to renew the entire sheet than only a part depending upon the conditions. Carbon and low-alloy steel sheets may be cut with a torch or carbon arc; stainless steel cannot be readily cut with the oxy-acetylene torch but may be cut by the oxy-arc process. If any of these methods are used the possible fire hazard involved in flammable insulation is eliminated by first boring holes in the sheet and soaking the insulation with water. After the damaged section has been removed the insulation can be replaced with non-flammable material. Damaged stainless steel sheets may be removed by cutting the spot welds with a chisel. Such sheets can often be straightened by hammering or rolling after removing them from the structure. Torn sheets can frequently be straightened, arc-welded and ground cheaper than they can be re-

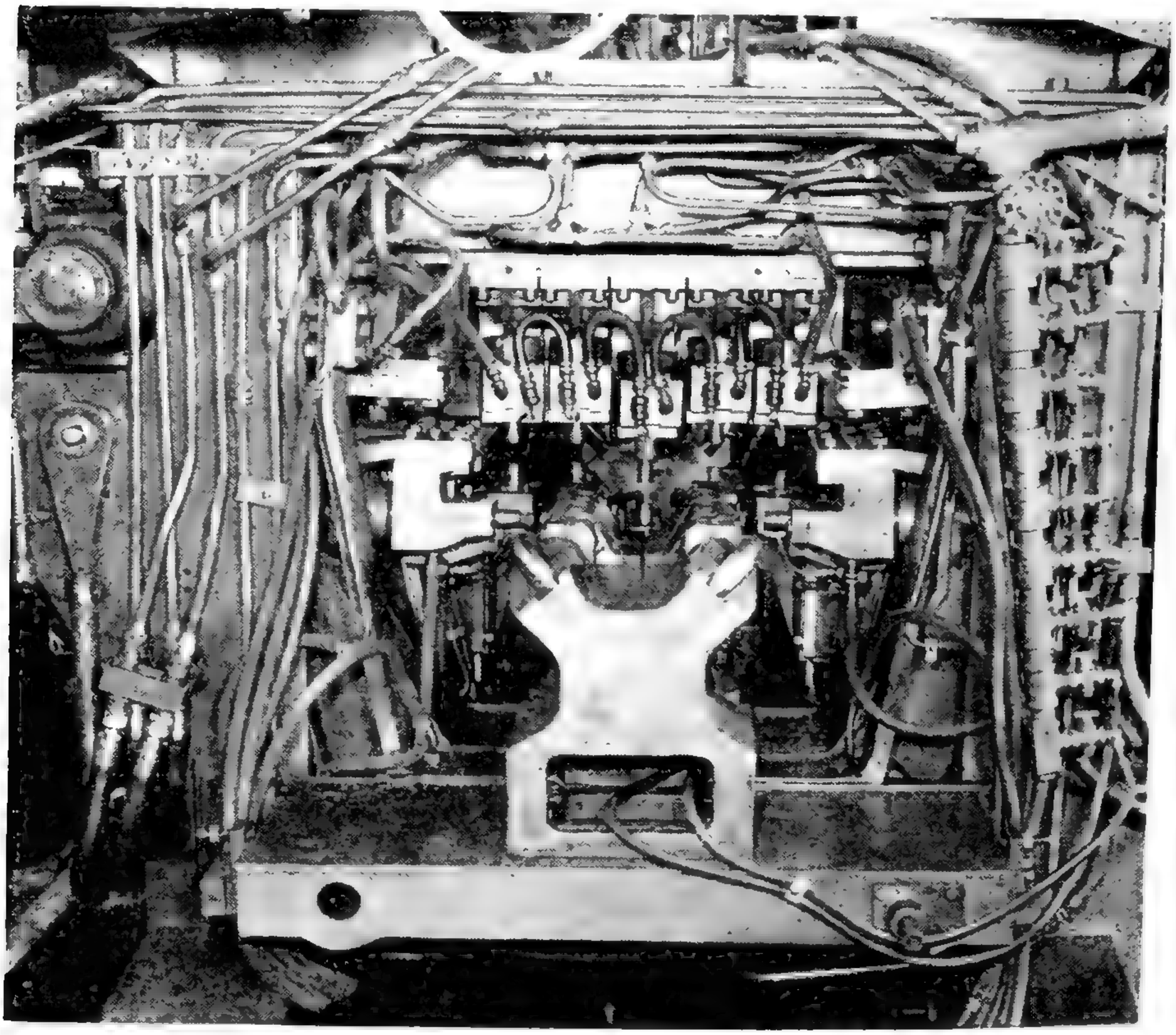


Fig. 22.—Special Automatic Center Sill Welding Machine

2700 welds of 20,000 lb. shear strength are made in less than 4 hours.

placed, especially on irregularly shaped sections. In arc welding stainless steel it is desirable to use a chill block or water quench on the reverse side whenever possible to minimize warpage and reduce carbide precipitation. The same procedure may be followed to advantage with carbon or alloy steels although it is not so essential. With thin sheets it is helpful to tack a backing strip to the new piece (or repaired piece) to facilitate welding the joint. If the joint occurs at a post or horizontal frame member no backing is needed. Brazing or braze-welding should not be done on stainless steel because of the danger of carbide precipitation, but may be useful with carbon or low-alloy steels.

When a spot-welded stainless steel member of a structure is damaged and must be removed, this can be done with a stripping chisel. Where pieces are of the same thickness, or the piece to be stripped is thicker than the sound structure, it becomes necessary to reduce the thickness of the material to be stripped in order that the separation will not pull slugs from the piece to be saved. After stripping, the surface of the structure must be ground smooth and the new parts rewelded with new spot welds located between the old welds.

Occasionally when portable machines cannot be used due to insufficient clearance or lack of access to one side of the work the replacement parts may be attached by plug welds or, if of light gage and not highly stressed material, the parts may be poke welded.

Recently use has been made of inert-gas metal-arc welding to make plug welds, working from one side of the sheet. Further development may prove this to be useful for car repair work.

Figure 23 shows how body and vestibule posts, window sills and letter boards are repaired by splice patching or complete renewal by welding in a manner similar to sheets. Soft soldered roof sheets may be replaced by welded sheets using the roof car lines as a backing. This makes an economical repair job that gives superior service. Older type roofs with clerestory present some special problems, but nevertheless repairs can be made readily and satisfactorily by welding.

The underframes of damaged or wrecked cars are repaired according to the standard methods outlined by the AAR. In many cases parts of cast steel platforms and draft castings are repaired by welding forged sections to them, either as reinforcements or replacements. Worn buffers and diaphragm castings are restored by welding.

Various truck parts such as worn pedestal legs are built up, bolster chaffing plates and wear plates on cylinder levers are attached by welding and pedestal and roller-bearing, outer housing liners are also similarly fastened. Fractures in truck frames are repaired or reinforcements added by welding in accordance with a specified procedure or the wearing face may be surfaced with weld metal.

Air-conditioning equipment, supply and battery boxes, and tanks fastened under the car may be replaced or repaired by welding. Corrosion, abrasion and impact from stones makes the service conditions to which these parts are exposed very severe.

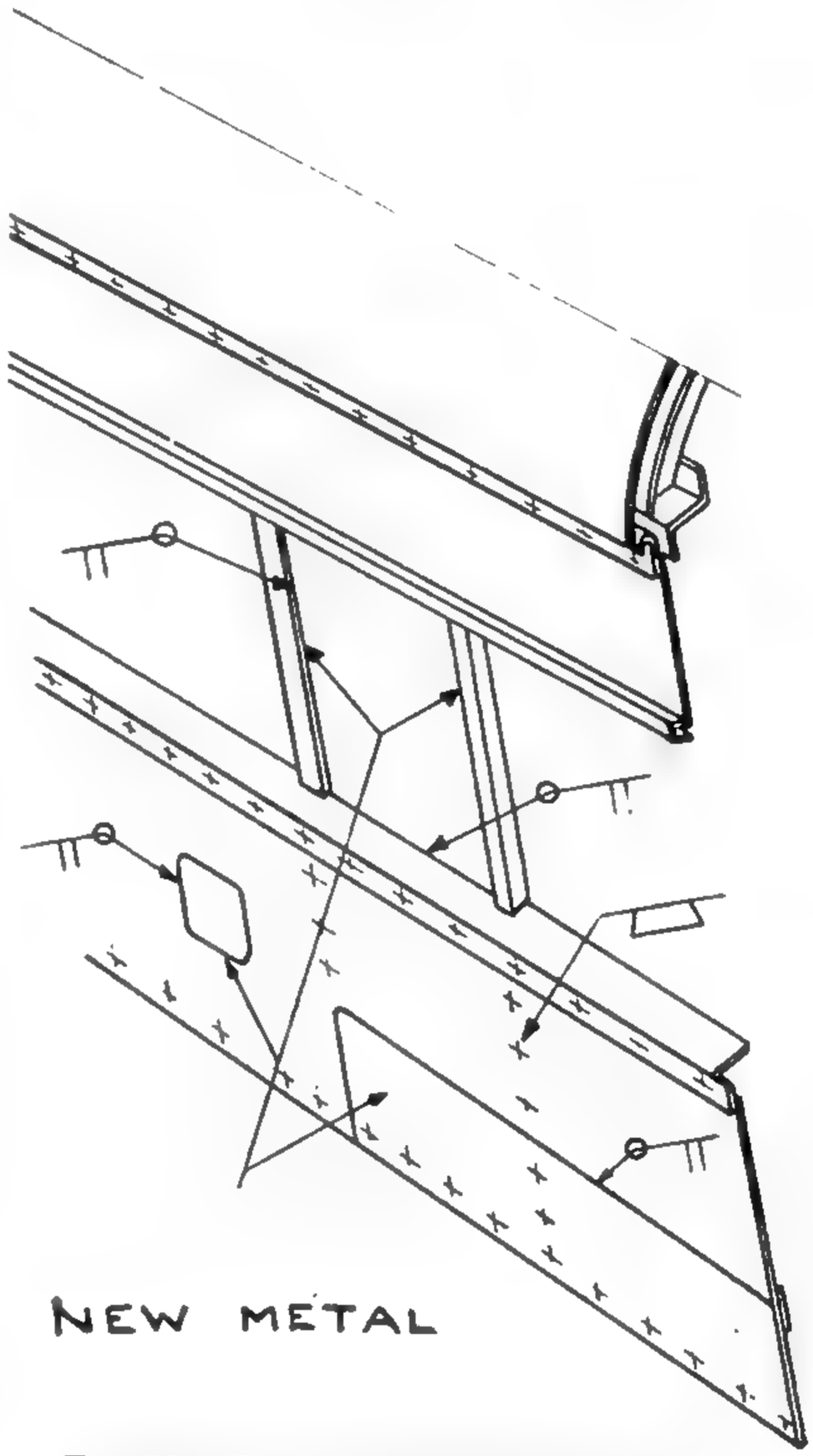


Fig. 23.—Typical Passenger Car Repair

Non-skid steel plates for steps and platform floors are welded to eliminate not only the expense of drilling, tapping and application of screws, but also the trouble involved in removing the screws after they have been corroded in service. Wooden or old-style bolted and riveted steps may be replaced to advantage with a welded design.

FREIGHT CARS

General

The demand today by the railroads for lighter weight equipment is being met through the use of light gage, low-alloy, high-tensile steel. Such steel is somewhat more costly per pound than ordinary mild steel but has definite advantages that account for its utilization. In many cases reduction in weight without loss of strength, in others increase of strength without change of weight and in still others increased corrosion resistance is the basis of selecting low-alloy high-tensile steels.

Conditions involved in car designs employing these new materials favor fabrication by welding rather than by riveting. Welding permits the designer to use reduced thicknesses of low-alloy sheets thereby reducing weight without sacrificing strength, after due attention is given to more exact stress analysis and design with a view to obtaining the full benefit of the superior properties of these steels. Except for the center sill, the framework is composed largely of shapes pressed or sheared from sheets and plates. All types of cars, box, flat, hopper, gondola, and some special cars such as covered hoppers, are built in this manner.

There are no codes applying to freight cars analogous to those for passenger cars. The principal limitation is the AAR clearance lines which insure unrestricted movement of cars over all rail lines.

Car Bodies

Car Sides.—In building freight cars, many forms of manual arc, automatic arc and spot welding are employed, but spot welding is limited mainly to box cars. The development of multiple-spot welding equipment, so arranged that a large number of spot welds can be made simultaneously, has reduced the time required to fabricate car sections such as sides and roofs. In one method of manufacturing car sides the main sections, consisting of 15-gage sheets, are assembled and spot-tacked on a copper-faced jig. These sections are then indexed through a spot welding machine and all welds from the top plate down to the upper side sill are made at one time. The sheets are joined together by series welds, all timed by a single timer. Individual electrodes are used to join the sheet to the top plate, this being a weld between 15-gage steel and a $^{5}/_{32}$ in. top plate, and similarly to weld the side sheet to the upper element, the joint in this case being between 15-gage and $^{3}/_{16}$ in. material. The sections are then moved to a post welding machine where the posts, $^{1}/_{8}$ in. Z's pressed from sheets, are welded. Pressure sequence welding is used. Two electrodes are used simultaneously, one on each side of the center-line of the side. Two welds are thus made at the same time beginning at the middle of the section and moving progressively toward the top and bottom of the side. Heat controls compensate automatically for the large change in impedance as the welding approaches the outer edges. Ignitron tube contactors and electronic timing devices are used to insure uniformity of the welds and an automatic voltage compensator takes care of any fluctuations in line voltage. A section of a box-car side is shown in Fig. 24.

In another method of making sides (also roofs) the welding is done with a different type of multiple-spot welding equipment. In this case, through the use of a multiple distributing switch in the secondary or heat-generating circuit, the entire group of electrodes is put under pressure simultaneously. These electrodes act as a self-contained clamp at each weld location and remain in position through the entire cycle of the welding sequence. The facilities for applying the correct pressure on all electrodes simultaneously and having it applied (without time delay) until the various welds are sufficiently cool, produce a very clean, strong joint of uniform quality. Such a multiple spot welding machine is made up of the following principal elements:

1. A constant pressure hydraulic system for platen lift and electrode shift.
2. An adjustable pressure hydraulic

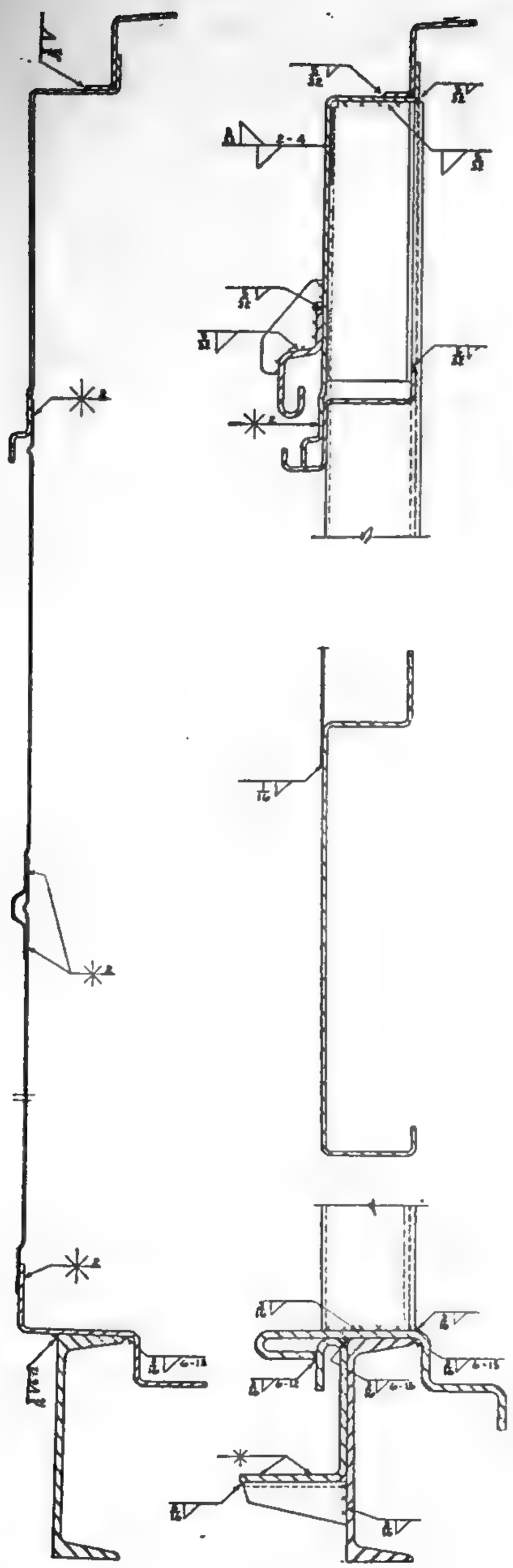


Fig. 24—Section of a Welded Box Car Side

system to supply all electrode cylinders.

3. Multiple-mounted transformer units to supply multiple-electrode groups.

4. Primary current supply to each transformer group through ignitron contactor and mechanical timing cams.

5. High-speed secondary distributing switches.

6. An indexing jig-car covered with a secondary copper top.

7. A water-cooling system to transformers, secondary switches, distribution cable and electrodes.

These automatic, multiple welding machines consist of an upper moving platen, upon which is mounted the multiple electrode setup adapted to roofs and a second set up for sides. Preliminary to spot welding, the side framing members are assembled in an accurate jig and firmly clamped into position. After the spot welding has been completed on the half sections of a car side they are joined together at the doorway to make a complete side unit. If the door does not extend to the top of the car it is necessary to weld in a section of top plate or join the two sections together if one long top plate has been provided to span the door opening. A Z or channel pressing is placed back of the joint to serve as a stiffener as well as a backing for the weld. The side-sill section for the doorway may be spliced with butt welds, or, as it is in later methods of construction, the entire side-sill channel may be included in the assembly of a side before the door and door framing are attached. Doors are commonly made of low-alloy, high-tensile steel spot-welded together. Some strengthening gussets are usually provided at the floor line of the door posts or extra strong posts of special form may be used at the doorway. Figure 25 shows the details of a car side.

Not all builders use spot welding for constructing car sides; some prefer to use arc welding instead. Special jigs have been made to permit the use of submerged arc welding for this work. The longitudinal welds at the top and bottom of the sides are made with one machine and the vertical joints with another. The side sheets are butt welded where they meet at a post, but at the intermediate posts the sheets are attached by adjusting the submerged arc welding so that the welds penetrate completely through the

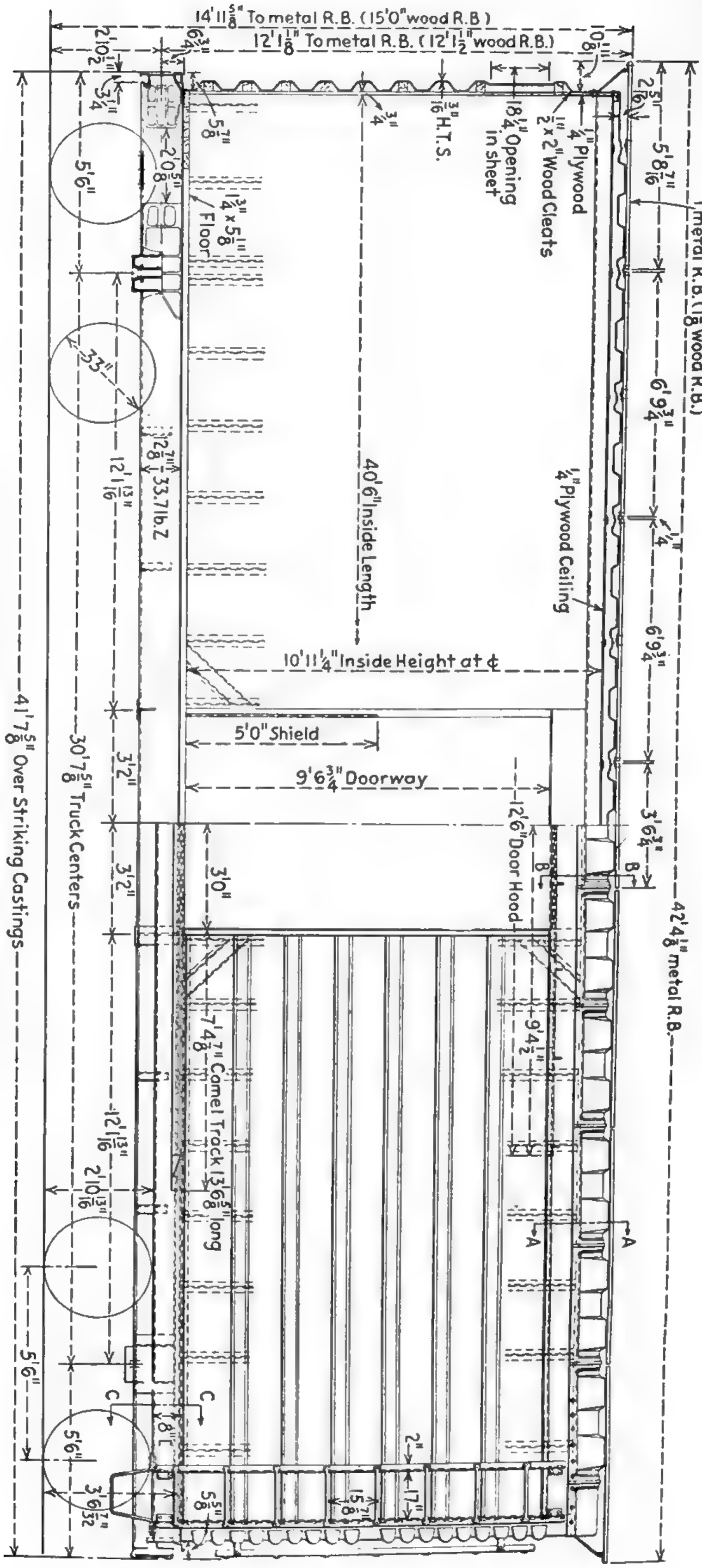


Fig. 25.—General Arrangement of Parts of Welded Box Car Side

sheet and into the post. The light material used for sides makes high-speed welding possible, speeds of ten feet per minute being exceeded.

Roofs.—Freight car roofs may be fabricated on a multiple spot welding machine as indicated, using low-alloy, high-strength steel but some manufacturers arc weld the roofs. Such roofs are pressings of 14-gage galvanized, copper-bearing steel extending the full width of the car. The sections are assembled so that the flanged edges produce an edge joint. Welding of the joints may be done with covered electrodes or by carbon-arc welding using a silicon-bronze welding rod. The longitudinal edges of the roof may be riveted or arc welded to an auxiliary angle. Any pinholes in the transverse welds are found by inspection from the interior after the roof has been placed on the cars and are then repaired.

Ends.—Car ends are made by assembling two corrugated pressings in a horizontal jig and joining them by arc welding. Corner caps, and lumber door if used, may be fitted and welded in the same jig. The end post is welded after the end has been removed from the jig and turned so that the inside faces up. The end posts are welded at the tops of the corrugations ($1^1/_2$ in. welds) on the inside and along the entire length of the flanged edge on the outside as shown in Fig. 26. Studs are welded at the bottoms of the corrugations to hold the wood fillers to which the wood end sheathing is attached. Recently stud welding has come into general use for attaching these studs. (See Chapter 14.)

Underframes

The underframing of freight cars is very similar for most types of cars and differs but little from that of passenger cars except it has no *platform casting* at the ends. Center sills consist of two Z bars weighing about 35 lb. per ft. Some are mild steel and others are low-alloy, high-strength steel. Common practice is to weld the two bars together by the submerged arc process in a jig provided with air-operated clamps and with sufficient camber to just offset the bending tendency produced by the continuous weld. A complete penetration weld is not required in this joint.

Bolsters, cross bearers, cross ties and tie plates are attached to the center sill. The bolsters are box-like members fabricated from four plates by welding and may be individual units or have one common cover plate. When the bolsters are made separately they are attached to the center sill in pairs, one on each side. Many bolsters have been attached to the center and side sills with rivets for convenience in making repairs, but in recent practice the trend has been to attach them by welding. Cross bearers are strength members of the underframe and consist of a top and bottom cover plate welded to a vertical web plate. They connect the center sill to the side sill on each side of the doorway. These parts are fabricated by welding and are of low-alloy, high-strength steel the same as the bolsters. Floor supports, numerous brackets and other attachments are welded to the center sill or adjacent parts.

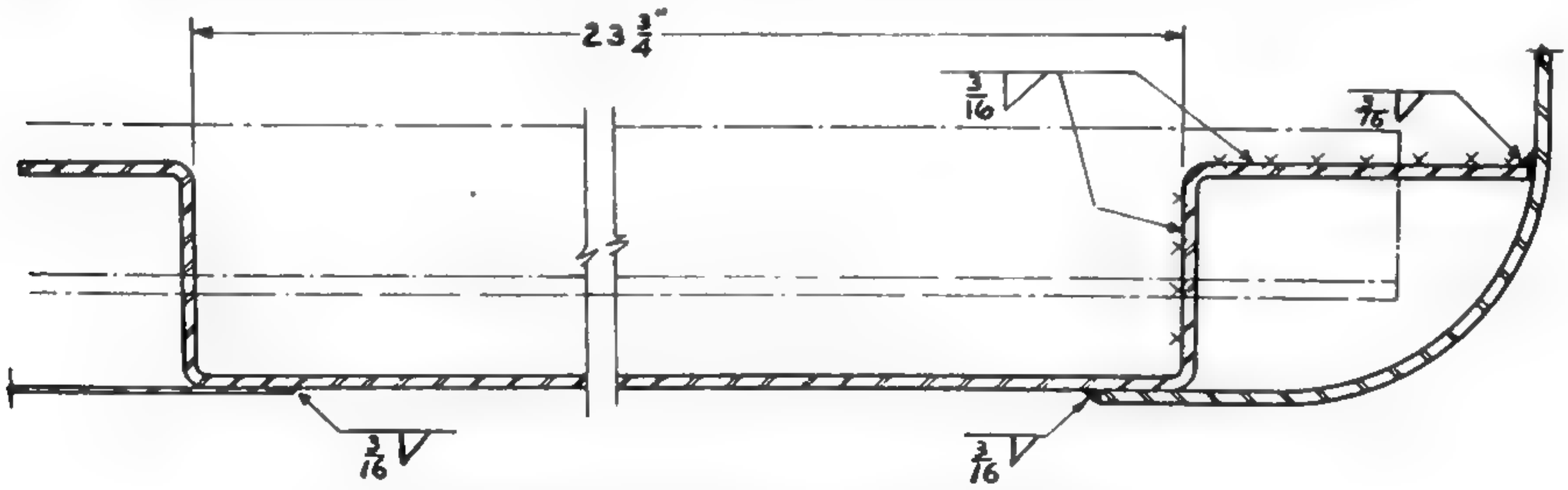


Fig. 26.—Section Through Corner of Welded Box Car

As a result of the scarcity of steel castings during the war, some car builders designed center fillers and striking blocks of welded low-alloy, high-strength steel plates to replace the castings. The welded substitutes were even better adapted for attachment to the center by welding than were the castings and are now in common use.

The manufacture of freight cars is fre-

quently carried out on a production line similar to those employed in automotive work. Parts are prefabricated as units or joined in subassemblies ready to be fed to the assembly line. Since large numbers of units are made, this makes it possible to justify rather elaborate jigs to permit as much downhand welding as possible. Certain jigs have been mentioned above but many others are used. Bolsters and cross bearers are made in jigs as are center fillers and strikers. Roof and side jigs are quite large and clumsy and are not arranged so that all welds can be positioned. Jigs for fabricating gondola car sides are in a similar class but fortunately most welding on these is done in the horizontal position. Some car builders use a jig for the entire underframe and arrange it so that the frame can be tilted 45 deg. either way, thus eliminating most of the welding in the vertical position. All of the jigs mentioned above are built special for the job by the car builder or railroad. Thousands of box cars like the one shown in Fig. 27 have been constructed.

Inspection of New Cars

New cars may be inspected by representatives of the railroad purchasing the equipment or by commercial inspection companies. With the exception of welded tank cars, on which X-ray inspection of the shell joints is required, and the squeeze test on passenger cars, the inspection procedure for arc welding follows fundamentally that set forth in Chapter 42.

Repairs to Freight Cars

Freight cars requiring replacement of parts, due to mechanical damage or corrosion, are repaired by methods very similar to those used for passenger cars. The AAR Rules of Interchange provide detailed instructions, as well as restrictions, for repairs by welding. Freight car parts may be cut off and restored to the original shape in the blacksmith shop, if not damaged too severely. After straightening and repairing, they are welded back on the car. Riveted parts may be welded through the rivet holes in certain cases. Considerable care and

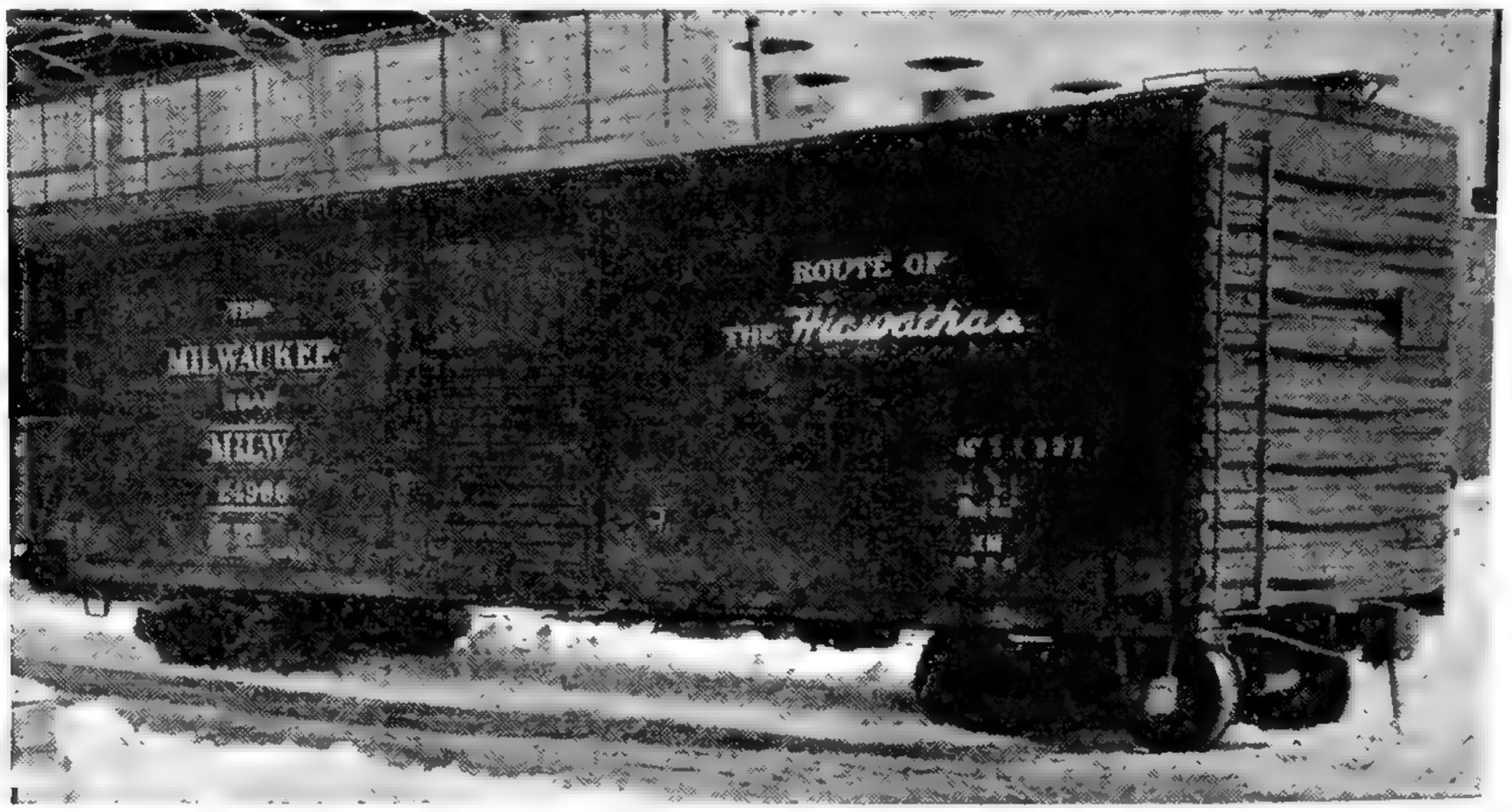


Fig. 27.—Welded Box Car

judgment must be exercised in combining riveting with welding. The inherent stiffness of welded joints made on a riveted car body may lead to failure of the welds, or of the welded parts, by overloading.

Malleable iron castings on freight cars must be brazed, not arc welded. Important steel castings such as side frames, yokes and couplers may be welded, subject to certain AAR restrictions, and are normalized after welding.

TANK CARS

Fabrication

The fabrication of tank cars, such as shown in Fig. 28, by arc welding had a long uphill struggle, but a number of years ago special authorization was ob-

tained from the ICC for welded tank cars for experimental service. Since then the AAR Committee on Tank Car Construction has recommended to the ICC some permanent specifications covering the construction of arc-welded tanks and a large number have been built. Many of the early cars were for petroleum service and were of 8000 or 10,000 gal. capacity.

With the extensive development of pipe lines for petroleum products the construction of tank cars for handling those commodities has decreased, but has been more than offset by the demand for welded tank cars by the chemical industries. The smooth interior of the welded tank lends itself well to the lining process that is frequently required for the transportation of chemicals. The necessity for using rivets for safety appliances to meet the ICC requirements presents something of a problem, especially for lined tanks, but also for the unlined ones because of the danger of leaks developing around the rivets.

The application of welding to tank cars has not enabled the car designer to reduce the weight materially but there is some reduction due to the elimination of laps and the weight of the rivet heads. Some further weight reduction has been gained by applying welding to the underframe structure.

The construction of the tank body follows quite closely the methods used in fabricating locomotive boilers, particularly in the case of the heavier shells ($1^1/_8$ in.) used for liquefied petroleum gases maintained under pressure in transit. Joint details, at least for machine welding, are very similar to those used in boilers. The joint between dome and shell, however, differs, the dome being simply welded to the shell without any reinforcement.

Submerged arc welding is used very extensively on steel tanks and on the underframe for all types of tanks. Inert-gas metal-arc welding is used in the construction of aluminum tanks. The circumferential seams for the heads as well as the longitudinal seams are welded both inside and out. (Details of submerged arc welding and inert-gas metal-arc welding will be found in the Chapters, 12 and 13.)

Tank cars may range in size from about 32 to 48 ft. overall length and up to nearly 90 in. in outside diameter. The ordinary steel tanks are made from three plates. The bottom third of the tank shell is made from a $^7/_{16}$ to $^1/_2$ in. plate, the top two-thirds being made from two plates $^5/_{16}$ to $^3/_8$ in. thick. The ends are made from $^1/_2$ in. plate. Special tanks, as mentioned above, may have much heavier shells. Tanks range in capacity from about 6000 to 16,000 gal., the latter size having been constructed in recent years for some railroads for handling Diesel fuel oil.

Fig. 28.—Single Compartment Insulated Tank Car

Inspection and Testing

ICC, *Specifications for Tank Cars Having Fusion-Welded Steel Tanks,* Class 103-W, requires that all longitudinal and circumferential joints be X-rayed. This code also requires that the tank be stress-relieved as a unit after all the attachments to be joined to the structure by welding have been welded in place. These requirements are very

similar to those for a pressure vessel built to the ASME *Unfired Pressure Vessel Code,* Paragraph U-68. These inspection requirements naturally place a heavy cost burden on the welded tank, but certainly provide adequate insurance that it is safe for the heavy-duty service to which it will be subjected.

RAILWAY TRACK WELDING

Arc and gas welding have been used for many years in the Maintenance of Way Departments of railroads for the repair and reclamation of many materials previously removed from track and replaced with new parts. Many items repaired by arc and gas welding have a longer service life than do the new parts. This part of the chapter outlines in a general way some of the major applications of welding in maintenance of way work, and especially rebuilding rail ends. The nature of the welding, the varying conditions under which it is performed, and the types of materials involved are such that standard codes are not applicable.

Materials

The chemical composition usually conforms to one of the following:

Open-Hearth, High-Carbon Steel Rail

Nominal Weight, Lb./Yd.	Composition, % C	Mn	P (Max.)	Si
70–90	0.64–0.77	0.60–0.90	0.04	0.10–0.23
91–120	0.67–0.80	0.70–1.00	0.04	0.10–0.23
121 and over	0.69–0.82	0.70–1.00	0.04	0.10–0.23

Manganese Steel

Element	*Composition, %*	
Carbon	1.00[a]	1.30[b]
Manganese	12.00	14.00
Silicon	....	2.00
Phosphorus	....	0.10
Sulfur	....	0.05

[a] Min. [b] Max.

Repairs to Rail Ends

One of the most widely applied welding operations is building up battered rail ends, this being common to practically all railroads in the United States. The life of rail in track can be greatly lengthened and riding conditions materially improved, thereby reducing maintenance costs and damage to the rolling stock by providing a smooth transfer across the joint between rail ends.

Gas Welding.—The following gas welding procedure, used by one of the Class I Railroads for rail ends, is presented as an example of one that has given satisfactory results over a period of many years. Arc-welding methods are also used and will be discussed later.

Before proceeding with the welding of battered rail ends it is important to correct any unsatisfactory conditions in the joint support. Bolts should be tightened and worn angle bars should be replaced if:

1. An 0.006 in. thickness gage can be inserted between the rail and bar fit.
2. The bar is drawn in against the web of rail.
3. The bar surface is badly bent.
4. The bar is cracked.

The most satisfactory and economical results will be obtained by welding out-of-face* when 50% of the joints in any stretch are battered or mismatched 0.30 in. or more, and by welding locally where a small percent of the rail is badly chipped, battered or mismatched, the latter condition being brought about by replacing failed or broken rail with new rail of the same weight so that its end does not match the end of the worn rail against which it is butted. The economic factors considered in determining what rail ends should be repaired by welding are: the general condition of the rail; the kind, amount and speed of traffic over the rail; probable life in the location in question and the possibility of use in secondary lines. The minimum and maximum limits of batter on rail ends to be welded are dependent upon the factors mentioned above, but, in general, the following limits will produce the desired results: no minimum depth is recommended for high-speed main tracks not previously welded or end-hardened; a limit of 0.030 in. or more is recommended for secondary lines and slow-speed freight lines, with no limit on depth of weld, and no welding to be done beyond the last hole in the angle bar.

The procedure followed in marking joints for welding is shown in Figs. 29, 30 and 31. It is desirable to use a 24 in.

* A railroad term meaning to weld each joint as you come to it.

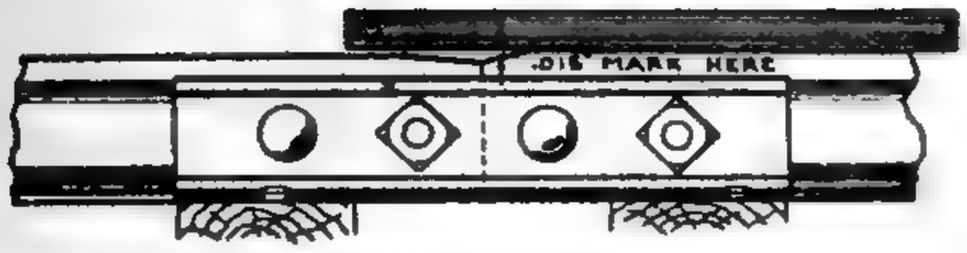


Fig. 29.—Method of Marking High Rail

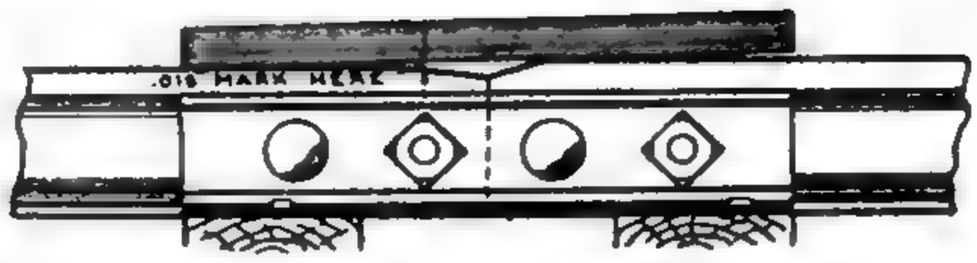


Fig. 30.—Method of Marking Low Rail

straight edge together with a taper gage to determine the depth and the length of the weld that will be necessary. A chalk mark is placed on each rail end to indicate the length of weld that should be applied. In marking joints to be finished with a flatter, the straight edge is manipulated so as to eliminate measuring the bend in the angle bar or a low joint (Fig. 31), but if the joints are to be finished by grinding, longer welds are necessary to prevent the abrasive wheels from digging in at the end of the weld and the mark should be placed where the thin end of the taper gage, approximately 0.006-in. thick, can be inserted between the straight edge and ball of rail. Whether to finish with a flatter or grinding depends upon the condition of the rail, location and other factors.

The size of the welding tip necessary may vary from one which consumes approximately 60 cu. ft. of oxygen per hour for lightweight rail to one which consumes approximately 80 cu. ft. per hour for heavier weights of rail. A neutral flame should be used for heating the rail in preparation for application of the weld metal, for melting out loose or laminated metal and for reheating to smooth with a flatter or to make a cut with a hot-cut chisel. A slight excess of acetylene should be used for application of the weld metal to insure against an oxidizing flame and for fusing weld and base metal at the thin end of the weld or smoothing out the weld metal after application.

The weld metal is applied to the rail ends in small patches to make parallel deposits lengthwise of the rail. The deposit is shaped while hot with a hammer to produce the proper contour and is finished with the flatter if the joint is not to be ground subsequently. Open joints require somewhat different procedure from tight joints and insulated joints require a still different procedure. A welded bent joint is shown in Fig. 32.

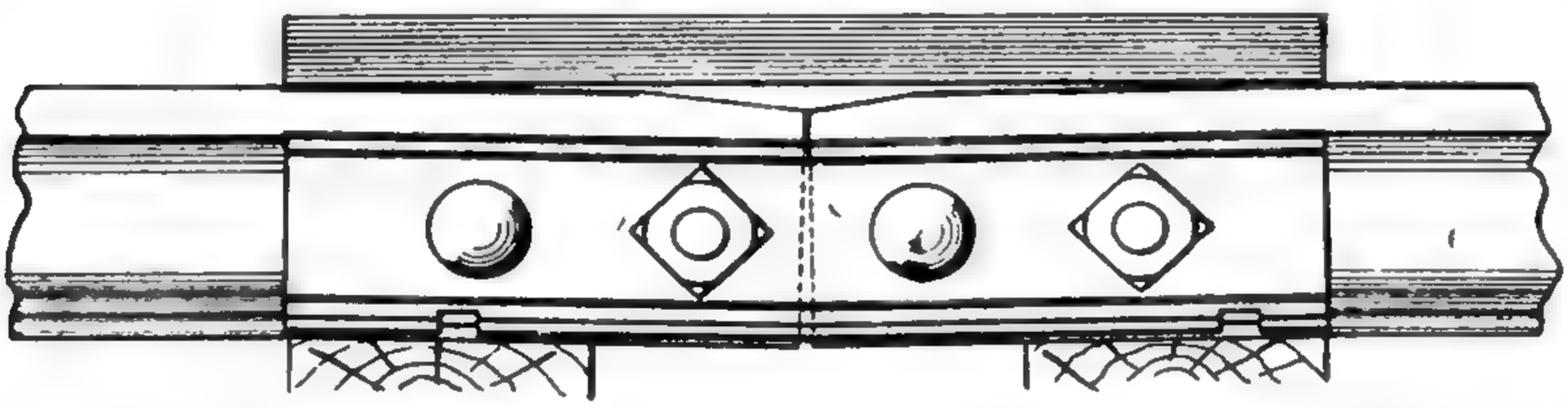


Fig. 31.—Low or Bent Joint

Composition of Rod.—The chemical composition of the welding rod should be such that it will produce a tough deposit of weld metal that is resistant to batter from wheel loads, but which will not crack by mechanical hardening to which it is subjected in service. The analysis of a suitable rod is: carbon 0.45%, manganese 1.09%, silicon 0.52%, chromium 1.10%. A maximum Brinell hardness of 375 for the deposited metal without heat treatment is most desirable. Deposits

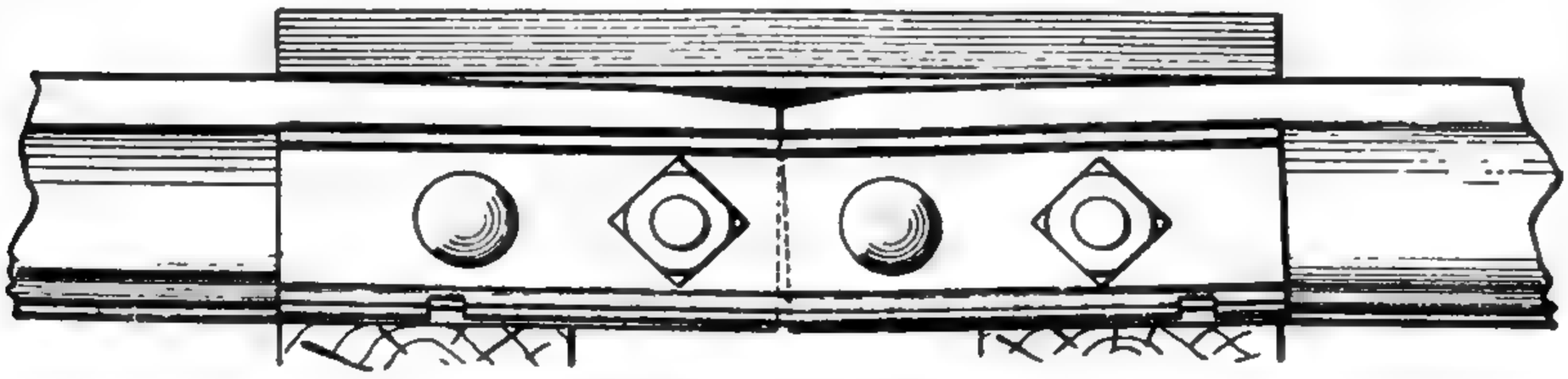


Fig. 32.—Finished Welded Joint

having a higher hardness number may cause chipping or cracking of the deposit or result in secondary batter (batter beyond the weld area) which is much more difficult and costly to repair.

Welding rod, 1/4 in. diam. by 36 in. long, is suitable for the average rail end welding work, but for light deposits a rod of 3/16 in. diam. by 36 in. long may be used.

Arc Welding.—Rail ends are also rebuilt by arc welding, but the procedure differs in that preheating is necessary and postheating (tempering) may also be employed.

The preheating temperature ranges from 500 to 700° F. depending upon the technique used. This is ordinarily done with propane using either air or oxygen for combustion. Welding is done with either an a.c. or d.c. arc using plain high-carbon electrodes, or in some cases high-carbon alloy electrodes. The weld as deposited may have a hardness from about 325 to over 600 Brinell. In the case of the harder deposits postheating is used to reduce the hardness to about 350 to 400 Brinell with the hardest zone being near the rail end. It is desired to have a hardness gradient from the top of the rail decreasing to the normal rail hardness of around 240 about 1/4 in. below the surface. Postheating temperatures of 1000 to 1100° F. are customary and in subfreezing weather retarded cooling for two or three minutes is obtained by placing an insulated cover over the joint. Surface and cross grinding operations are identical to those used with gas welding.

Welding Open-Hearth Frogs

The economic factors to be considered when determining whether or not to weld a frog are: the general condition of the frog; the kind, amount and speed of traffic over it; the accessibility to a welding unit; and the probable life of the frog at the location in question. The most economical and satisfactory results are obtained by: welding frogs before the batter exceeds 3/8 in.; with slight batter, if they have not already been hardened, when frogs are being welded at locations not easily reached by the welding unit; before the frog has become so badly battered that filler blocks will not hold wing rails and point rails in proper relative positions; and before frog point bolt holes have become elongated and frogs are badly bent.

Batter measurements are taken between the thin end of the frog point and the section where the point and the wing rail sections are approximately the same width as shown by the wear. This is done by placing a straight edge (Fig. 33) across the frog, one wing rail to the other, and measuring the distance between the bottom of the straight edge and inside top edge of the wing rail. Consideration must then be given to the conditions mentioned above to determine if the frog should be welded. In general, it can be stated that a frog is not in a satisfactory condition for welding if: the bolts are loose; the frog is badly surface bent; it is not properly supported by ties; the guard rail is out of adjustment, allowing side wear on the point; the angle bars on the joints at the ends of the frog are loose.

In welding frogs and crossings a carefully established welding procedure is followed, similar to that for building up rail ends. The welding tip used should be one that consumes from 60 to 70 cu. ft. of oxygen per hour on wing rails and 50 to 60 cu. ft. of oxygen per hour on the thin end of the frog point. The torch adjustments for the welding flame should be the same as outlined for rail end welding.

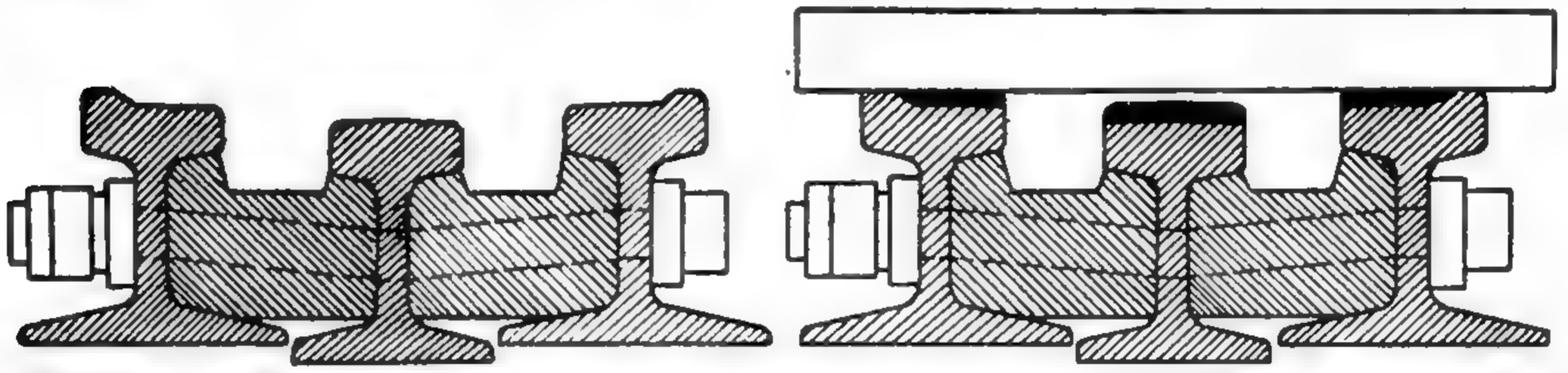
In the application of the weld metal a small flame is used and the metal added in patches 3 to 4 in. long, keeping the rod in the center of the pool. Work is started on the heel end of the frog at the point of wheel transfer to the wing rail. The first bead of each patch is applied along the inside edge of the wing rail and the bead carried toward the toe end of the frog. The welder then works back to the starting point allowing the weld metal to overhang on the inside edge. The procedure is repeated until sufficient metal has been deposited. The weld is then hammered smooth from the edge of the weld metal to the inside edge. The final operation is to trim with a hot-cut chisel and smooth with a flatter. The opposite wing rail is built up in the same manner.

On frog points welding is started at the heel end, working toward the thin end. When a frog point is more than 3/16 in. lower than the wing rails, it is built up so that it will be not more than 3/16 in. below the surface of the wing rails. Then

a suitable runoff is made in the direction toward the heel of the frog, keeping the frog point level to the thin end. The thin end of frog points should be welded before the frog is allowed to cool.

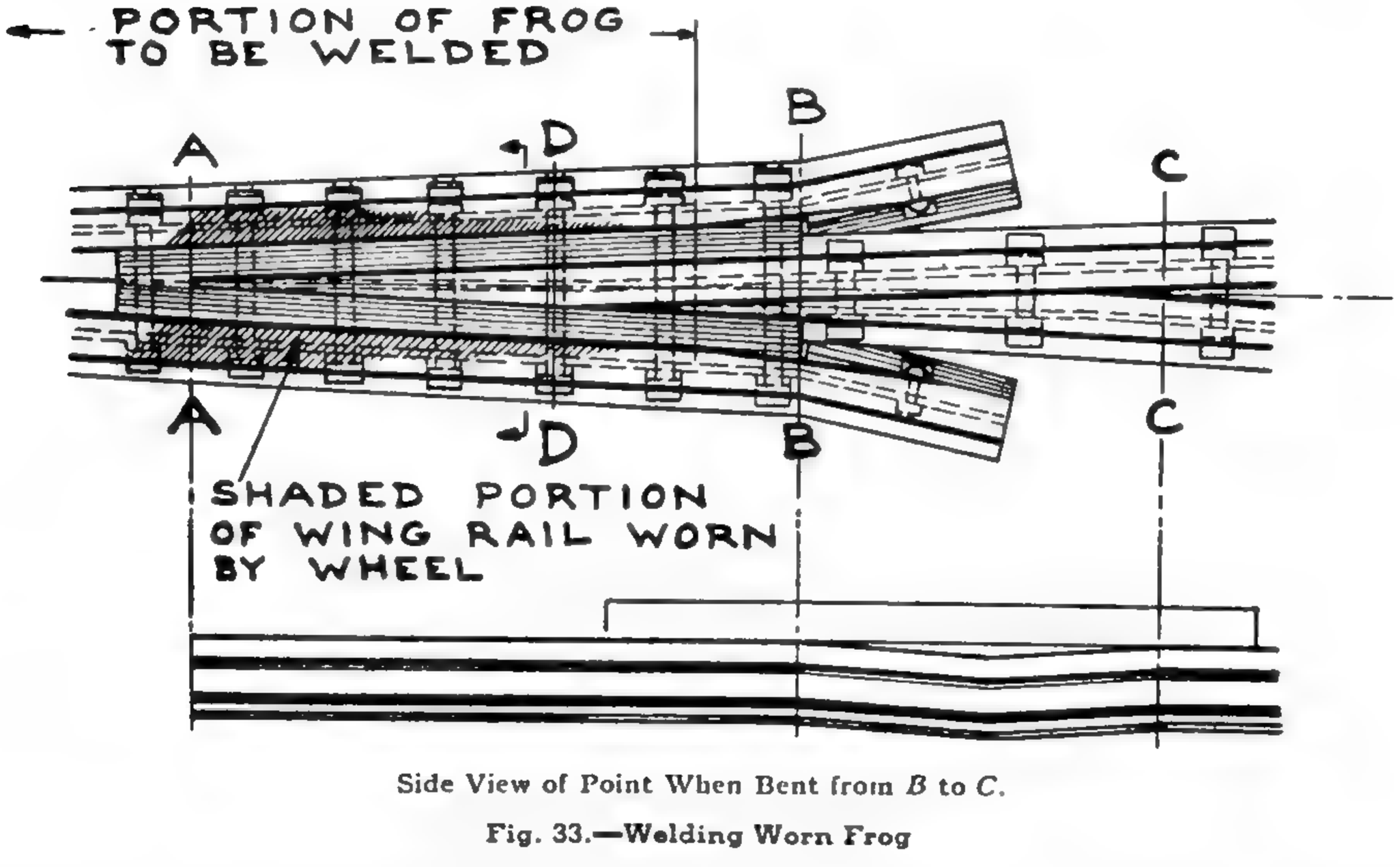
It is economical to weld frogs in position unless the traffic is so heavy that not even one frog can be completed per day. This practice involves the least investment for frog replacement and it is not necessary to weld the rail at the frog ends each time the frog is welded. When welded in position in the track the frog can be welded to suit the location. There are disadvantages, of course, in that the welding costs may be increased because of delay on account of traffic, weather conditions and damage due to heavy loads passing over red hot frogs. Figure 33 shows a worn frog with a bent point before and after welding.

The welding of frogs at a centralized shop has advantages because of the better facilities for handling, straightening the parts and replacing bolts. In addition there is less delay in the welding operations and there may be a reduction in welding costs effected by the use of generated acetylene. The disadvantages of taking frogs out of track and bringing them to the shop are the cost of removing and replacing them and the increased investment involved in carrying a number of replacement frogs. An attendant disadvantage lies in the necessity of making every frog so that it will be suitable for any location which involves the extra cost of changing the rail at frog ends to match the rail on the frog. Warping can be corrected by applying heat along base of frog rails to counteract heat applied to top surfaces, but clamping one frog to



Section of Worn Frog Before and After Welding.

Plan View of Worn Frog



Side View of Point When Bent from *B* to *C*.

Fig. 33.—Welding Worn Frog

another with blocks between is the most satisfactory when work is done out of track.

Crossings

In the repair of crossings the procedure outlined for welding of frogs should be followed but there are additional precautions to observe. The rail should be inspected for incipient cracks at the junction of web and ball and defective sections replaced in high-speed track. In slow-speed track the cracks may be welded if regular inspection can be made. Riser rails should be built up to match running rails and the top surface of such rails kept separated by beveling with hot-cut chisel. On a crossing where traffic causes uneven wear, the rail with the heavier traffic should be built up to make a smooth wheel transfer. The lighter traffic rail is built up or reduced to match the heavier one.

Switch Points

Switch points may be welded in or out of track according to what is expedient for the conditions.

The welding rods used for oxy-acetylene welding of rail ends are also satisfactory for frogs, switch points and crossings.

Rebuilding Manganese Frogs and Crossings

High manganese frogs and crossings must be repaired by arc welding.

The general procedure for inspection, marking, measuring batter and preparing for welding is very much the same as that outlined above for open-hearth steel frogs. It should be pointed out, however, that frogs and crossing sections should not be welded if they are badly cracked longitudinally in filler sections, or across wing or point sections when such cracks extend into fillers and cannot be removed so that the weld may be started at the bottom of the crack. In preparation for the application of weld metal the following precautions should be observed: all surfaces upon which metal is to be applied should be clean; loose or laminated metal and all cracks in wing and point sections must be removed. If the oxy-acetylene torch is used to remove defective metal enough clearance must be allowed to permit reaching all oxygen-cut surfaces with a grinder. Defective material may also be removed entirely by grinding but the oxygen-cutting torch is more economical and satisfactory if followed by grinding. Weld beads are run longitudinally with the wing and point sections to restore proper height and allow enough metal for finish grinding. Each bead is peened after application of each one-half electrode and the section kept as cool as possible by intermittent welding.

Proper grinding of a frog or crossing section is as important as the preparation for, and the application of, the weld metal. This involves removal of overflow metal, restoring proper height and contour.

Satisfactory repairs can be made to cracked sections by the application of nickel manganese applicator bars. Progressive cracks in the base sections can be stopped by placing these bars across the crack and welding them to the casting. Where necessary to cut or grind through the manganese section, welding these applicator bars at the bottom of the opening or across a crack will in most instances prevent a crack from progressing upward through the deposited weld metal.

The remarks made about open-hearth frogs, with reference to field or shop welding, apply to manganese frogs as well.

The chemical composition of the welding rod should be such that the deposited weld metal will have properties equal to the base metal. The copper molybdenum type of manganese steel, nickel manganese steel and ordinary Hadfield manganese steel are all used. Bare electrodes are more economical, produce satisfactory results for average work and are especially good when filling cavities where it is difficult to free the weld metal from the heavy slag. Covered electrodes are most satisfactory for work where the weldability of the base metal is not good; for welding cracks and for the application of a thin deposit of weld metal such as the top layer of the surface to be finished by grinding. See Chapter 31B.

WELDED RAILS

The standard rail length for American railroads is 39 ft. with weight per yard ranging up to 155 lbs. The conventional method for joining these rails is an angle bar assembly with either four or six bolts per joint. While improvements have been made in joint design, it is still the

weakest point in the track structure. Recognizing this, many railroads have employed one or more of several welding processes to weld rails together, thus producing solid rails that are longer than 39 feet.

Aside from the structural weakness of the conventional rail joint, there are economic factors. The steadily rising costs of labor and materials have focused attention on the reduction in the number of joints as means of reducing such costs. Railroad studies for years have centered on increasing lengths of rail with cost reduction as the goal. In the past forty years, the standard rail length has increased from 30 to 33 ft. and finally to 39 feet. Official studies by railroad engineering committees have been made on the economics of 45-, 60- and 78-ft. rail lengths. In addition to these studies, another official committee was set up to evaluate installations of rail that have been welded into extremely long rail lengths. This rail in effect is continuous.

Exhaustive tests of butt welds were made by different procedures, the welds being subjected, day and night, to severe rolling load fatigue tests, following a procedure similar to that used in the extensive rail investigations by the University of Illinois, and simulating the nearest approach to actual service conditions in track. To further assure a high-quality weld, extensive experiments were made with various methods of stress relief. This procedure has developed butt welds which stand up under the severe condition of a 65,000-lb. wheel load. The welds supported as a cantilever, Fig. 34 (top), were subjected to six million passes of the above load. They were then mounted as a simple beam, Fig. 34 (bottom), and six million additional 65,000-lb. wheel loadings applied without any sign of failure, equivalent to many years of heavy wheel loads in actual service.

Rails as light as 100 lb. and as heavy as 131 lb. have been welded. Ballast for continuous rail ranges from locomotive cinders to limestone and trap rock. Welded rail is also laid on open trestle bridges in lengths over 1000 feet. Traffic carried over welded rail ranges from freight only to predominantly passenger traffic. Welded rail is on main line open track where passenger trains run 80 miles an hour—freight trains above 60 miles an hour. Welded rail is installed where traffic goes in one direction and where it goes in both directions. In brief, welded continuous rail produced by one process or another is located where it is subjected to just about every service condition. In some instances, welded rail was located to provide a test of its performance under selected conditions. In general, however, the site was chosen for the purpose of improving maintenance or of eliminating a situation that was breeding trouble for maintenance forces.

In such cases it has been found more economical to carry out the welding at convenient points and move the rail by a

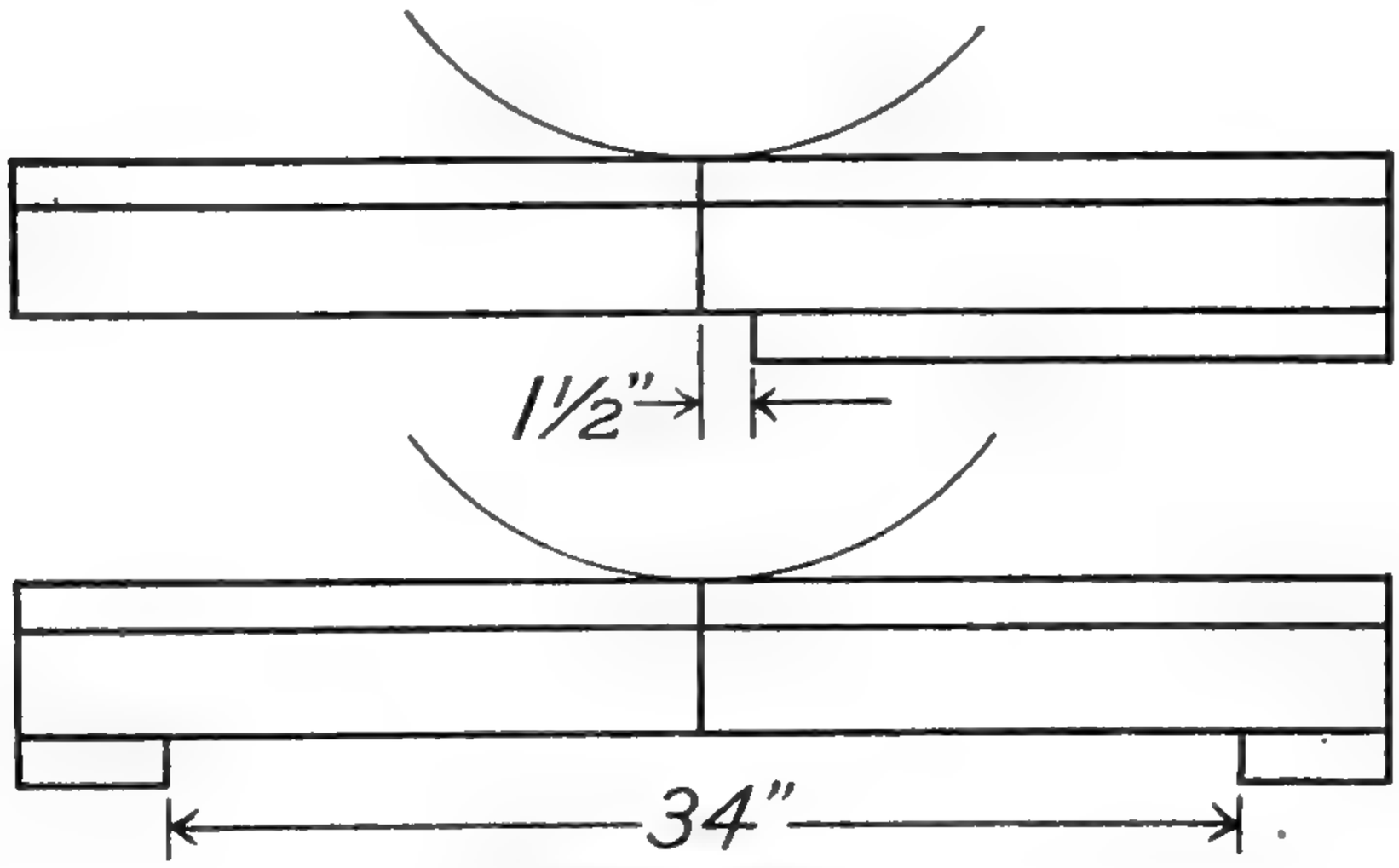


Fig. 34.—Welded Rail Test Joints

method appropriate for the lengths desired or the layout of the tracks. Continuous rail is very flexible and can be readily handled. In some installations, the welds have been made alongside of the track. This has the advantage of allowing the welded rail to be installed in place in long enough lengths to eliminate subsequent closure joints. At the same time there are obvious difficulties in that the work may be done on narrow shoulders, in open cuts, in tunnels or on bridges.

Semi-Automatic Pressure-Gas Welding

Semi-automatic pressure-gas welding was first introduced in 1938. The equipment used for this process is described in Chapter 7. In preparing rail ends for welding, approximately $^1/_{16}$ in. is removed to eliminate rust and any irregularities as received from the mills. If the rails are delivered from the mills with ends ground square, it is only necessary to use a light polishing disc to remove any light rust. It is more usual though to receive the rails without special mill work and ends are prepared by abutting two rails together and running a power-driven saw blade $^1/_{16}$-in. thick through at the point of juncture. Surfaces to be welded are wiped off with a solvent such as carbon tetrachloride at the time they are placed in the welding machine.

The rails are forced together in the welding machine and the oxy-acetylene flame heats a few inches of each rail end to about 2250°F. The combination of the hydraulic pressure and the application of heat produces the pressure-weld and forms a bulge at the weld called the upset. In the case of 90-lb. rails, the rails move toward each other about $^3/_4$ inch. Above 90 lb. this movement is $^7/_8$ inch.

When the required upset is reached, the flames are immediately shut off and the pressure held for approximately one minute. The rail clamps are then released, and the welded rail is moved out of the machine.

Trimming.—After welding, the rail is pulled by winch over rollers to the trimming station where the bulge or upset is removed by a manually-operated cutting torch. Cutting machines are also being used to hold and guide three cutting torches that speed up the operation and give a closer cut. A close, accurate cut speeds up the subsequent grinding operations.

Normalizing.—This is done in a special machine having a heating head arrangement similar to the welding machine. There are no clamps in this machine and the heads oscillate further to encompass the weld and heat-affected zones. The trimmed and still hot weld area enters the normalizing machine where the temperature is raised to 1550°F. which is above the upper critical. The normalizing temperature is fixed by the use of temperature pellets at the beginning of each day's run and subsequent welds are timed from this established cycle.

Grinding.—Grinding produces a smooth running surface at the weld area. Various types of gasoline or electrically-driven grinders are used to smooth up the top and sides of the ball, the sides of the base and to remove the weld seam from the web, and bottom of base and ball.

Figure 35 shows a finished rail weld.

Oxy-acetylene Butt Welding of Rails (Hand Method)

While the more mechanized methods were being tried, manual oxy-acetylene welding was being used to weld rail for use at street crossings, station platforms, tunnels and turntables. In order to obtain satisfactory results in the gas welding of rail ends the following preparations are essential:

(*a*) If in track, at least $^1/_4$ in. expansion must be provided between rail ends for cutting operations, or the rail cut before lining and applying angle bars.

(*b*) Base, web and ball of both rails are cut to form a small V, consistent with the depth or width of sections to be welded.

(*c*) All slag and scale are removed with hand hammer and chisel.

(*d*) Angle bars are applied leaving $^3/_{16}$ in. between rail ends and the top section of the bar on the side of the V in the web is cut away between center bolt holes.

(*e*) The bolts are tightened and the rails gaged to make proper alignment.

The welding procedure followed in oxy-acetylene welding is as follows:

(*a*) The ball of both rail ends is heated, using two torches when available.

(*b*) Application of weld metal is started at the junction of web and ball, making such application from the under-

side of ball and extending down on the web of the rail about $^3/_4$ inch.

(*c*) Then welding in center of ball at bottom of V is started, working first toward one side and then the other, with two torches being used after the weld metal is high enough on V to permit.

(*d*) The weld metal is kept extended well over the edge of rail.

(*e*) A high-tensile rod is used about one-half way up the V on ball of rail and a rail-end welding rod on the ball from approximate center to the top of the ball of rail.

(*f*) The weld is finally smoothed with a hand hammer and the angle bars removed.

(*g*) The web is welded from one side (both sides if two welders are available) starting at the bottom of the base.

(*h*) The base is welded with one welder working on each side of rail and when this is finished the angle bars are applied and the bolts tightened as quickly as possible.

(*i*) The top surface of rail is finished by trimming off overhanging weld metal on sides of the ball and smoothing with hand hammer and flatter.

Two welders should be used, where possible, each using a torch tip which consumes from 50 to 60 cu. ft. of oxygen and acetylene per hour. When only one welder is available the above size tip is satisfactory for the base, web and part of the ball of the rail, but a tip which consumes approximately 70 cu. ft. per hr. is needed to complete the weld on the top of the ball. A cutting tip with a 0.055-in. diam. orifice should be used for veeing rail ends.

Fig. 35.—Finished Pressure-Gas Welded Rail Joint

When the rail ends are to be butt welded out of track the same general preparations and procedures are followed as for welding the rails in track. When the base weld is completed from the top and angle bars have been applied and tightened, the rail should then be turned on its side and melted out at the line of the weld. Then the necessary metal can be applied to bring the surface back to level.

Flash Welding of Rails

Preparation and Clamping of Rails.—In preparing rails for flash welding, the ends are cleaned and the scale is removed at the point where the current clamps engage the rail. Care should be exercised in clamping the rail ends in the machine to insure accurate alignment, as misalignment in the machine will tend to introduce undesirable irregularities in an otherwise smooth track.

Capacity of Machine.—A machine, suitable for flash welding the rails used most generally today should have a transformer capacity of 750 kva. with a secondary voltage up to 14 volts. The upset pressure should be a maximum of 75 tons.

Welding.—The welding process consists of three phases:

1. *Preheating,* covering the initial period during which the rail ends are heated by a series of successive flashes accomplished by repeatedly bringing the ends of the rails together and then separating them slightly. This preheating covers a period of approximately $1^1/_2$ min. for 131-lb. rail. In preheating, the rail ends are brought to a temperature which will support continuous arcing or flashing.

2. *Flashing* is a continuous arcing or burning of the metal, as the rail ends are steadily moved nearer together. In effect, the movement equals the rate of burning of the metal. This flashing period is approximately $^1/_2$ min. for 131-lb. rail.

3. *Upsetting* covers the short interval (approximately 5 sec.) during which the flashing is terminated by butting the rail ends together with a pressure of approximately 10,000 psi. The welding current is switched off immediately following the completion of the upset. Total loss in rail length due to metal removed by flash and upset is approximately $1^1/_4$ in. per weld.

Stress Relief.—During the process of flash welding, stresses are set up in the immediate vicinity of the weld. Stress relief to correct this condition is accomplished by heating the weld and the adjacent rail metal in an oil furnace up to a temperature of 1200° F. followed by slow cooling controlled by an insulated hood.

Flash Removal.—The flash or excess metal should be sheared off and ground down below the small notch in the weld to eliminate any notch effect and the top surface and sides of the head should be finish ground to the exact contour of the adjacent rail.

Thermit Welding of Rails

Details of thermit welding as applied to railroad rails will be found in Chapter 19.

Problem of Expansion.—Taking into consideration the theoretical factor of linear expansion of metal, the problem of expansion of long lengths of rail in track is not as complex as might be expected. Theoretically, total movement in expansion and contraction of a mile of rail unrestrained under a 100°F. temperature change should not be less than 40 in. and might exceed 60 in., but forces are applied to restrain this expansion. Considerable restraint arises from friction between the rail and tie plate and this is augmented by conventional rail anchors. Additional restraint is obtained by the joint fastenings at the ends of long rail.

When continuous rail is laid midway between temperature extremes, say between 50 and 60°F., the range of temperature variations capable of creating stresses is about cut in half, and the maximum internal stress accordingly is reduced from 19,500 to 9750 psi. This is a small percentage of the tensile strength of rails and practice has shown that this stress can be controlled by rail fastenings now used on conventional rail.

Advantages of Welded Continous Rail

Briefly, the advantages of continuous welded rail are as follows:

1. It greatly reduces the cost of maintaining track in proper line and surface.
2. It eliminates joint batter.
3. It eliminates the need for replacing angle bars, bolts, nut locks and signal bonds.
4. It eliminates cost of renewing joint ties.
5. It provides a continuous, safer track signal circuit.
6. It eliminates impact components at joints, greatly reducing damage to bridge structures, roadbeds, rolling stock and lading.

Hardening of Rail Ends

Requirements.—Hardened areas of rail ends must be tough and have sufficient

depth of hardness to provide longer service life. They should be of sufficient hardness to retard wear and, at the same time, wear down uniformly with the balance of the rail and, finally, they should have a pattern that permits a uniform transition to the unhardened surface. Investigation in the early 1930's showed that sufficient hardness could be reached by heating the rail ends and then quenching them in water. However, uniform results were hard to obtain and water quenching is not now approved by AREA. Uniform results can be obtained by having the larger mass of the rail itself act as the quench aided by an air blast.

Machine Method.—Machines of special design mounted on four-wheel trucks are used. Mounted on the machines are four sets of oxy-acetylene heating heads each with three large heating tips. Two sets of heads are on one end of the machine over one rail, two at the other end over the other rail. Thus the joints on both rails can be treated without lifting the machine.

After the torches are ignited the heating heads are moved laterally across the head of the rail by a hand-operated oscillating mechanism. This oscillation prevents the burning of the rail during the heating. The heated area on each rail end is shaped like a butterfly's wing with the longer edge on the gage side of the rail.

Rate of production under this procedure is about one joint per minute, including the time required to move from joint to joint. A Brinell hardness of from 340 to 380 is obtained with hardness extending to about $^1/_4$ in. below the running surface.

Cooling of the heating heads is obtained by means of a copper baffle plate spaced between the outside and inside tips.

There are two general methods for end-hardening rails in track. The first is to permit traffic to run over the untreated rail for a period of time. This permits some cold-rolling and allows angle bars to become seated in the fishing surfaces. The rail is then surface ground to equalize the height of abutting ends and the ends are beveled with a cross grinder. Following this the flame-hardening operation is performed.

The second and latest method is to flame-harden rail ends as the steel gang lays rail. This method is less costly because special flagmen are not needed and it is not necessary to protect signal bonds as the hardening operation precedes the rail bond installation.

Manual Method.—Thoroughly trained operators can also perform end-hardening with a manually-held, large capacity torch. A suitable baffle must be used to confine the heat to the proper pattern. The required pattern is developed by moving the torch in small circles on each side of the joint. The flame is kept from contact with the rail ends to avoid overheating the edges. While a correct time cycle for heating has been developed, results are still dependent upon the ability of the operator. Where an air-blast quench is used, a suitable fixture is required to direct the blast. Following the timed air quench the cooling of the joint is retarded for several minutes by covering it with an insulated cover. Figure 36*A* shows the flame-hardening machine, and Fig. 36*B* shows the hardened rail.

Flame-Hardening Open Hearth Frogs

The flame-hardening equipment used for this operation consists of a traveling carriage which supports a special water-cooled heating head using oxy-acetylene tips. The heating flame passes over the area to be treated at approximately 6 in. per minute. Only the area of the point and wing rails from the throat of the frog to the place where the wheels are entirely carried by the point are treated. Frogs treated in this manner wear evenly without warpage. The frog is immersed in a water tank constructed of sheet iron. The water level is maintained by an adjustable drain pipe, with fresh water being continuously introduced.

Frogs treated by this process have given more than four times as much service as untreated frogs in the same location. The cost of treating a No. 10-100 lb. frog, including the cost of handling the frog to and from the tank, is nominal. Since the underlying metal is unharmed, the frog can still be reclaimed by normal oxy-acetylene welding, after the treated area has been worn.

This same procedure is used to flame-harden other portions of the switch construction, such as the frog guard rails, special crossing frogs and switch point stock rails.

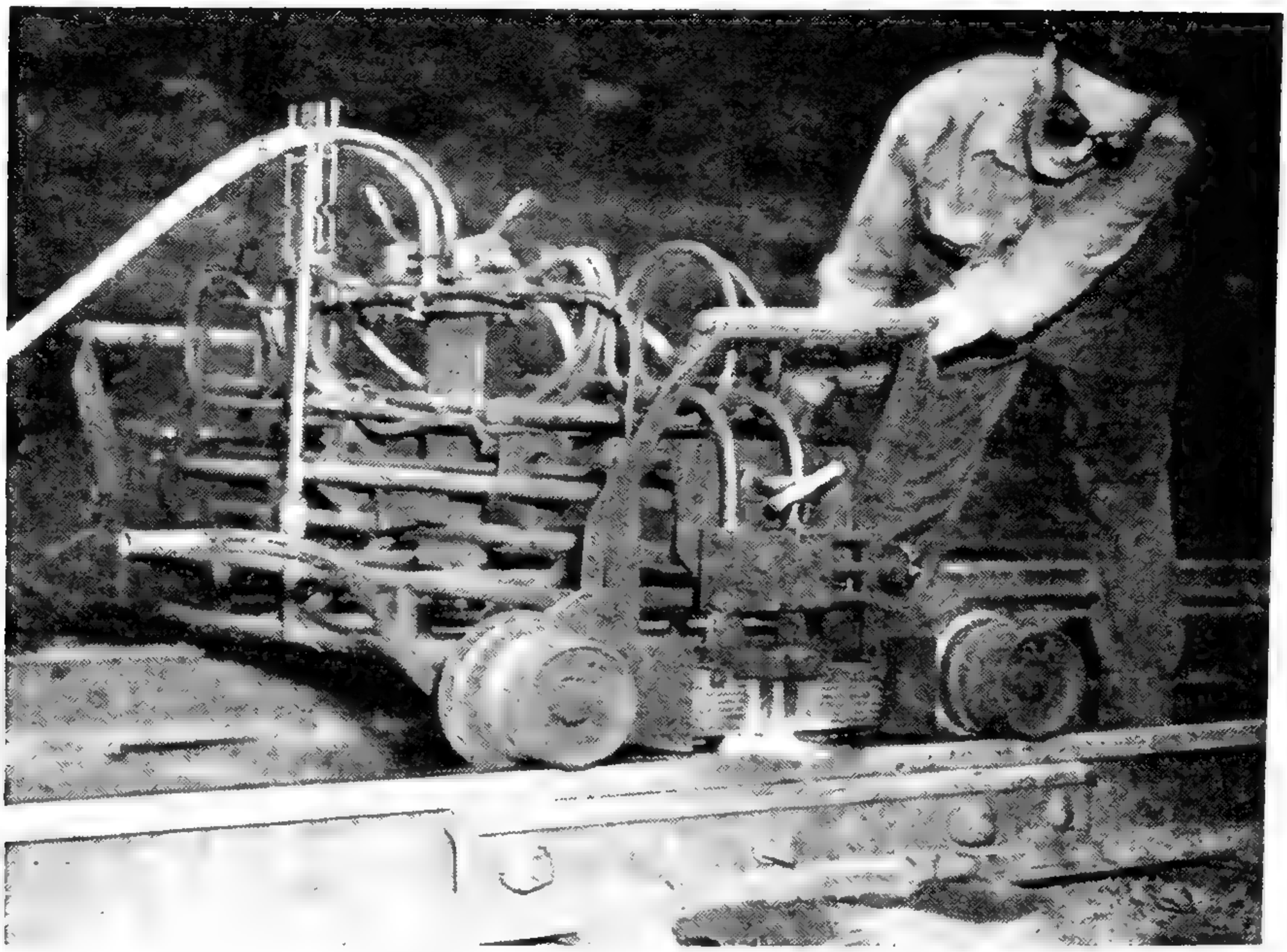


Fig. 36A.—Machine for Flame Hardening Rail Ends

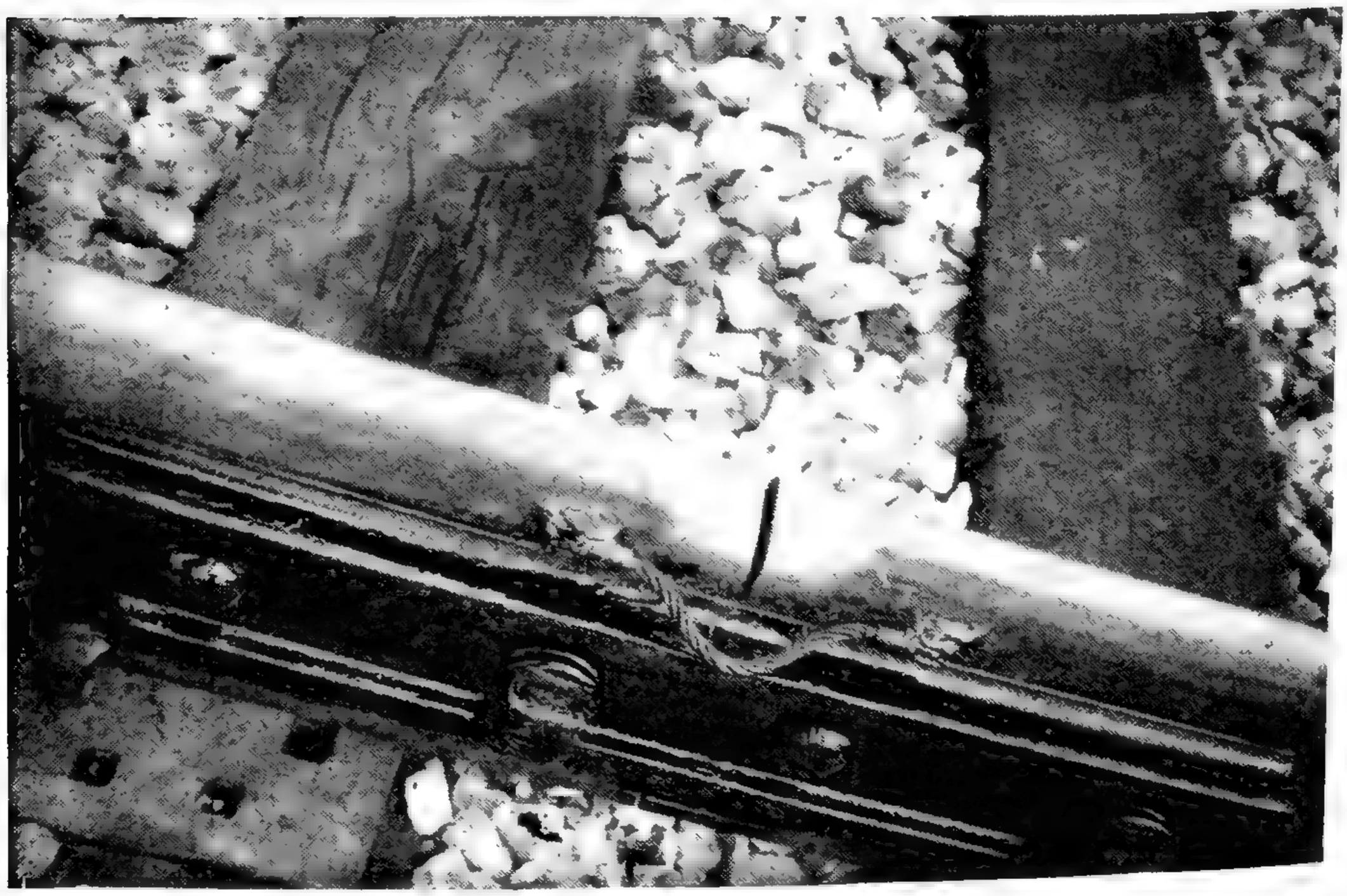


Fig. 36B.—Flame Hardened Rail Joint

STEAM PIPES ON LOCOMOTIVES, CARS, AND IN THE RAILROAD SHOPS

Locomotives

The wide use of both the oxy-acetylene and arc-welding processes by the railroads has naturally led to the use of one or both of these processes in the installation and repair of pipes on steam locomotives, cars and in the shops. Although welding is used extensively in such work, it is not always practicable to weld the lines, whether they are for steam, air, water or sand in their entirety. Provisions must be made to facilitate taking them down by the installation of screw joints at certain locations. Pipe lines must be removed to enable periodic inspections to be made as covered by the ICC regulations, and in some instances to facilitate repairs to the boiler or other parts if the pipe obstructs them. By careful planning, pipe line installations can be made in the individual classes of locomotives, whether they be the welded or screw type joints, so that they will be standardized on each class. The general practice on many railroads is to weld the following pipes:

All air piping on locomotives and tenders.

Exhaust pipes from air pumps and feedwater heaters.

Sand pipes with the exception of maintaining a screwed union near the end of the pipe or under the running board so same can be removed in case of derailment.

Gravity oil feed piping such as to elevator bushings and racks on stokers, stoker conveyor screw bearings on tenders.

Steam piping, air brakes and signal piping on the locomotive tender except that a threaded connection must be provided on the nipple at the rear end of the tender and also where the pipe connects to the flexible joint at the front of the tender.

All piping lines for oil on oil burning locomotives may be welded.

Extra heavy or double strength piping is used for steam pipe installation to air pump, air pump exhaust line, water heaters, ash pan flooders, headlight dynamos, steam train lines and blow-down lines. Oxy-acetylene welding is the generally accepted process on this class of work and welded pipe fittings are seldom used on locomotives. Pipes are bent to suit their location and direction and any connected pipe is welded to other steam pipe directly without the use of fittings. The injector delivery pipe may be welded except at its connection to the injector and the boiler cheek. Common practice on welded pipe is to provide screw joints or flexible connections at the receiving point and at the delivery end of the line.

While there is no rule in the ICC regulations prohibiting the use of welded joints within the cab on steam pipes subjected to boiler pressure, no welded joints are usually made on such pipes, either in the cab or in the brakeman's cupola located on top of the tender tank on some locomotives.

Copper piping for steam and oil generally has fittings attached by the use of soft soldering carried out in an oil or coke forge. In recent years there has been some trend toward the use of silver alloys for this work, or in some cases to eliminate the brazing operation and use only the bell type of joint on copper pipe.

Several advantages are derived from welding of the pipe as compared with the use of screw fittings. Engine failures naturally are reduced by the elimination of failures due to screw connections. Minor steam leaks at the threaded connections are eliminated; the pipes are less likely to break and there is less maintenance since there are no screw joints to be loosened by vibration.

Passenger, Baggage, Express and Freight Cars

Steam heat lines on passenger and baggage cars are extra heavy pipe and installations are commonly of the welded type. Steam heat lines used in connection with certain types of air-conditioning units requiring steam also have welded pipe as well as the interior heating radiators of express and mail cars. All air and steam piping on coaches, baggage, mail and express cars may have welded pipe up to the ends of the cars where steam or air hose and steam connections and angle cocks are located. The advantages of the welded design in pipe installations on this equipment are similar to those given for locomotives.

In Shops

Welding can be employed for the installation and maintenance of many pipe

lines within the railroad shops and contiguous territory. Some of the pipe lines on which welding may be used are the following: Piping in air compressor rooms and distributor lines to the various departments; exhaust lines; water supply lines, including those to wash rooms and toilets; fuel oil lines and heating lines within the fuel oil lines; all blowdown lines except drop lines where flexible joints are required; steam supply and condensate return lines for heating systems and water distribution lines except those used in drinking water. In most cases galvanized pipe with screw fittings is used for conveying drinking water.

It has been the experience of water service maintenance crews that the threaded connections on underground pipe, especially steam pipe in intermittent service, as well as the overhead lines in roundhouses are the first parts to be attacked by corrosion. Welding, of course, eliminates this source of trouble as well as that due to loose joints resulting from expansion and contraction of pipes in service.

Old locomotive flues may be utilized in place of pipes for such purposes as steam and air lines to depots and passenger train yards; for down spouts on depots, warehouses and shop buildings, thus effecting economies in installation and reduced maintenance. In general, welded pipe installations are far superior to the screw joint type of installation. Either oxy-acetylene or arc welding may be used on shop piping, depending upon the size and thickness of the pipe and the conditions under which it is installed.

BIBLIOGRAPHY

1. *Continuous Welded Rail,* American Railway Engineering Association Annual Reports, 1936.
2. *End Hardening New Rails,* Railway Engineering & Maintenance, February 1937.
3. *Continuous Welded Rail,* American Railway Engineering Association Annual Reports, 1937.
4. *Continuous Welded Rail,* American Railway Engineering Association Annual Reports, 1939.
5. *Welding in Tank Car Construction,* J. W. Sheffer, The Welding Journal, October 1940.
6. *ICC Code 103-W Specification for Tank Cars Having Fusion-Welded Steel Tanks,* 1940.
7. *Welding of Passenger Cars,* A. M. Unger, The Welding Journal. April 1941.
8. *Design of World's Largest Welded Flat Car,* H. Malcolm Priest, The Welding Journal, October 1941.
9. *Oxy-acetylene Pressure Welding of Railroad Roads,* L. Adams, The Welding Journal, November 1941.
10. *Design and Construction of Underframes for All-Welded Railroad Passenger Cars,* J. E. Candlin, Jr., and A. M. Unger, The Welding Journal, May. 1943.
11. *The All-Welded 5400 Hp. Diesel-Electric Freight Locomotive,* J. H. Hruska, The Welding Journal, August 1943.
12. *Welding as It Applies to Railroads,* Robert Moran, The Welding Journal, October 1943.
13. *Locomotive Parts, Fabrication and Welding of Bronze Bearing Surfaces,* J. W. Kenefic, The Welding Journal, October 1943.
14. *The Welded Locomotive Boiler,* E. G. Young, The Welding Journal, October 1943.
15. *ASME Boiler Construction Code, Section III, Rules for Construction of Boilers for Locomotives,* Am. Soc. Mech. Engrs. 1943.
16. *How Long Can a Rail Be,* Railway Age, February 12, 1944.
17. *Welding of Railroad Transport Equipment,* C. O. Druetzler, The Welding Journal, June 1944.
18. *Welded Railroad Rails,* Welding Engineer, November 1944.
19. *The Welding and Heat Treatment of Couplers and Other Car Parts,* John McMullen, The Welding Journal, November 1944.
20. *Arc Welding of Rail Steel,* C. B. Haynes, W. H. Graft and R. C. Spencer, The Welding Journal Res. Suppl., July 1945.
21. *Railroad Tank Cars of All-Welded Aluminum,* R. E. Haas, The Welding Journal, October 1945.
22. *Critical Shearing Stress in Skin-Stressed Box Car Sides,* V. L. Green and J. J. Drinka, Transactions ASME, October 1945.
23. *Flame Cutting, Flame Hardening and Welding on Railroads,* J. W. Kenefic, The Welding Journal, April 1946.
24. *Welded Rail—After 13 Years on the D. & H.,* Railway Engineering & Maintenance, June 1944.
25. *Modern Steels in Railroad Construction,* H. M. Priest, The Welding Journal, July 1946.
26. *Quantity Production of Railroad Passenger Cars by Resistance Welding,* A. M. Unger, The Welding Journal, October 1946.
27. *Welded Freight Car Construction,* R. L. Rex, The Welding Journal, November 1946.
28. *Locomotive Boilers—Welded Construction,* J. Partington, The Welding Journal, December 1946.
29. *The Shortening of Eyebars to Equalize the Stress,* The Welding Journal, Res. Suppl., December 1946.
30. *Low-Alloy, High-Tensile Steels, Their Properties, Workability and Weldability,* G. M. Huck, The Welding Journal, January 1947.
31. *Welded 50-Ton Boxcars,* Railway Mechanical Engineer, April 1947.
32. *70-Ton Covered Hopper Cars,* Railway Mechanical Engineer, May 1947.
33. *Assembly Line for Welded Cars,* Railway Mechanical Engineer, August 1947.
34. *Continuous Rail—A Challenge to the Engineer,* Modern Railroads, August 1947.
35. *A Note on the Shrinkage and Distortion of Welded Joints,* F. Guyot, The Welding Journal Res. Suppl., September 1947.
36. *Flame-Hardening Adds Life to Frogs,* Modern Railroads, September 1947.
37. *Problems in Resistance Welding Stain-*

less Steel Railway Car Structures, J. H. Van den Beemt, The Welding Journal, October 1947.
38. *Flame Hardening Locomotive Brake and Spring Rigging Pins and Bushings*, B. W. Covell, The Welding Journal, October 1947.
39. *Welding of Locomotive-Type High Pressure Boilers*, G. M. Trefts III, The Welding Journal, November 1947.
40. *New Developments in Railroad Maintenance of Way Work*, C. A. Daley, The Welding Journal, November 1947.
41. *Stress Analysis of Passenger Cars*, K. F. Nystrom, AAR Convention, 1947.
42. *End Hardening Rail Ends and Open Hearth Frogs*, Canadian Transportation, December 1947.
43. *General Service Box Car*, Railway Mechanical Engineer, December 1947.
44. *Welding in Car Repairs*, H. E. Gannett, Railway Mechanical Engineer, December 1947.
45. *The Evolution of Diesel Engine Blocks Weldment Design and Fabrication*, J. W. Owens, The Welding Journal, March 1947.
46. *AAR Rules of Interchange*, Issued Yearly.

CHAPTER 54

AUTOMOTIVE PRODUCTS*

INTRODUCTION

IN THE MODERN automobile, welding processes are the primary method of fabrication. There are approximately 8000 resistance welds in an automotive body and many automobile frames have from 300 to 500 in. of arc welding used in their fabrication. The amount of welding in any particular body, chassis or engine depends upon the detailed design. However, with present design trends, the number of welds as well as the number of parts fabricated by welding is increasing materially each year.

The automotive industry uses practically all of the common welding and allied processes of joining. Resistance welding processes are the most extensively used. However, manual arc welding, automatic arc welding, manual gas welding and brazing are widely used. The fabrication of many parts involves the use of furnace brazing using a hydrogen or cracked gas atmosphere and a copper brazing alloy or induction or resistance brazing with silver alloys. Inert- gas metal-arc welding is coming into use for certain special applications on light sheet metal.

The requirements of welded joints in automotive construction differ widely depending upon the part to which welding is applied. However, the following general requirements for automotive components will indicate the type of service requirements that welded joints must meet:

1. Fatigue resistance.
2. Rigidity in bending, torsion or both.
3. Corrosion resistance.
4. Freedom from leakage. (This requirement varies widely depending upon whether the part being discussed is a fuel tank, brake line or merely a part of the body structure.)
5. Good surface finish. (Associated with this requirement is the necessity for any welding process to provide joints requiring a minimum of finishing.)

There are a number of special conditions that are peculiar to automotive production and lead to somewhat different handling of welding problems when compared with methods used by many other industries. This is particularly true because of the high production rates found in the majority of automotive plants. For example, production of 5000 units per day requires an hourly production rate in excess of 330 if the schedule is to be met with two shifts totaling 15 hours. When the particular component is used in multiple quantities on one vehicle, the production requirements pyramid rapidly. For example, an eight-cylinder engine normally will have 16 tappets. Thus, for a production of 5000 engines per day a minimum of 80,000 tappets will be required. On a 15 hr. basis, this necessitates an hourly production rate of over 5300 parts. These high production rates materially influence the selection of the welding process to be used for the fabrication of automotive components. Obviously, manual methods requiring skilled welders and a relatively low output per man are undesirable. This accounts for the decided preference for the use of resistance welding which is found throughout the automotive industry.

Cost considerations are the determining factor in the selection of a fabrication method for automotive parts, and a saving of a fraction of a cent per part in either labor or material cost represents a large yearly cost.

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The high production rates required, together with the emphasis on minimum labor and material costs per unit, lead to the use of large quantities of specialized welding equipment capable of producing hundreds of welds in a single operation. For example, multiple spot-welding equipment is frequently designed to make over 100 welds per part on 300 or more parts per hour.

Obviously, the use of specialized equipment for either resistance or automatic arc welding necessitates extensive tooling changes whenever the detailed design of a part is modified. This requires a careful study in order to balance equipment replacement costs against the savings to be obtained by its use during any one year. It also requires that the equipment be designed so that changes to adapt it to the production of new models will be at a minimum.

This chapter on automotive products will outline briefly some of the methods used for the production of automotive components. However, only those methods which are currently in use and proved in production will be included

ENGINE APPLICATIONS

Engine Blocks and Heads

Repair of Castings.—Until recently, engine blocks and heads were fabricated entirely by casting. It was found that a relatively large number of imperfect castings were produced and that many of these can be satisfactorily and economically reworked by welding.

The types of defects which can be repaired satisfactorily by welding include misruns, laps, blowholes, cracks and porosity as well as tool gouges, mismachined dimensions, broken off portions, etc.

In general, careful control of this reworking is maintained so that the repairs do not in any way impair the serviceability of the part or materially affected subsequent machining operations. Faulty repair procedures can result in cracking, warpage, loss of strength, softening, etc.

A competent inspector is required for the inspection of cylinder blocks and heads. He must be familiar with the castings being inspected, the repair welding procedures and the areas in which repairs can satisfactorily be performed.

Table 1—Typical Materials Used for Automotive Parts

Part	Material Used
Engine Blocks and Heads	Alloy cast iron
Valve Tappets	SAE (1% C, 1.5% Cr) steel welded to SAE 1030 steel.
Valves	Exhaust valves: Stellite No. 6 deposited on cast 1% C, 16% Cr, 14% Ni steel
Muffler and Tail Pipes	Low-carbon or aluminized steel
Frames	Low carbon (0.25% max.) steel, 0.090- to 0.105 in. thick.
Rear Axle Housings	Low- or medium carbon steel stampings, cast steel or malleable iron.
Fuel Tanks	Terne plate
Propeller Shafts	Low carbon steel tubing welded to free machining, high sulfur SAE 1045 steel forgings
Wheels	Low carbon, rimmed or semi killed mild steel.
Body Panels	Low-carbon, cold rolled steel sheet for exposed sufaces and hot-rolled pickled and oiled low carbon steel for hidden parts. Occasionally higher strength SAE 950 material has been used.
Trim Materials	Straight chromium and chrome nickel stainless steels. Some aluminum is presently in use
Body Hardware	Although these items are often chrominum plated die castings which are not welded, considerable amounts of welded chromium-plated steel are used for horn rings, hinge stops, etc

MATERIALS

Because of the wide variety of materials used in welded components in automotive construction, only a brief summary of the more important ones can be given in this chapter. Table 1 shows typical materials used for various welded components.

It is necessary that he decide upon the necessity of the repair and the desirability of a repair as compared to producing a new casting. He must also make a preliminary choice of the repair method. The procedures for determining the location and extent of repairs permitted have been well established by most automotive manufacturers and are usu-

ally available in written form for the inspector's guidance.

The majority of defects are found by visual inspection of the as-cast blocks and heads after sandblasting. Other defects are found by hydrostatic testing or in a few cases by the *kerosene and chalk* method. Magnetic powder and fluorescent penetrant methods are occasionally used.

A number of factors dictate the selection of the specific method of repair welding best suited for a particular defect. Among these are the condition of the casting, *i.e.*, rough or machined; the location of the defect; the size and nature of the defect; the necessity of color match, etc.

The preparation of defective areas for repair welding may require the removal of metal to provide a groove which can be satisfactorily welded. Any sand present in the original defect is removed. Preparation may be accomplished by oxygen gouging, chipping or grinding.

The majority of repairs on as-cast blocks and heads are made by oxy-acetylene welding using a cast-iron welding rod. Preheating is required in order to prevent cracking from the localized expansion and contraction caused by welding. General preheat of the entire block or head in a furnace is necessary when an appreciable amount of welding is done in restrained portions of blocks and heads. This includes all areas except edges, corners, bosses, etc., where only local preheating has been found suitable.

In all repair operations on cylinder blocks or on other critical areas where extensive welding is required, the rate of heating and cooling must be slow enough to prevent cracking. In addition to the preheating it is usual practice to postheat the blocks after welding. The maximum temperature for this postheating operation must be selected so that it will not materially soften the particular cast iron being used; this will usually be in the 800 to 1100°F. range.

For other repairs on cylinder blocks, brazing is occasionally used instead of welding if color match is not required. This process is employed for defects on bosses, corners, edges, etc., in a manner similar to gas welding with local preheating. A lower preheat temperature is required and repairs can therefore be made with greater freedom from warpage and cracking.

When defects are found after the castings have been partly or completely machined, oxy-acetylene welding usually cannot be performed without excessive distortion, and, accordingly, some repairs are made using special arc-welding techniques.

On finished blocks, repairs of small sand holes are sometimes made in cylinder bores by one of two methods. Bare nickel electrodes are employed with both processes. One method, sometimes erroneously called *cold welding* or *battery welding,* involves use of a high amperage (approximately 350 amp.) with a sufficiently low voltage (6 to 12 volts) to make it impossible to maintain an arc. Batteries are usually used as a current source and the metal is deposited by a scratching action. Considerable skill is required to secure a good bond and a deposit free of porosity.

The second method is usually known as *intermittent welding.* Welding current is obtained from a special transformer wherein it is interrupted periodically by a contactor, thus preventing the accumulation of heat. This method is preferred by the majority of producers over the one previously described. Repairs can be made faster, the bond is better and the deposit is sounder.

Excess weld metal deposited in cylinder bores is removed by a special grinder that is designed to remove the reinforcement down to the original bore wall so that rehoning will finish the operation.

Metal arc-welding electrodes of the heavily covered type with pure nickel core wire are used for the repair of the small defects, machining errors, etc., on finished or semi-finished blocks and heads. These electrodes may be used for small areas in nearly all locations on castings, including machined surfaces. The weld metal is readily machinable and the heat-affected zone is small and may be machined with some difficulty. A preheat of about 300°F. aids in reducing this hardened zone but a local postheat of about 1000°F. is necessary to restore good machinability. Low amperage, alternating or reverse polarity, direct current is used. The weld beads are deposited in short lengths which are peened and permitted to cool before the next increment of weld is deposited. In some cases covered electrodes having Monel core wire are used for similar applications. In most cases, however, the use of

nickel electrodes has superseded the use of Monel.

Welding is used either with or without other repair methods. These supplementary repair methods include soldering, metallizing, use of sealants, and mechanical methods such as plugging, bushing, etc.

Fabrication of Blocks and Heads.—A recent advance in the use of welding was made with the introduction of the Crosley engine. The cylinder block and head of this engine are composed of steel stampings, steel tube cylinders and screw machine parts. These parts are furnace brazed into one assembly in a hydrogen atmosphere using a copper-brazing alloy The generator pulley, crankshaft pulley, fan pulley and water pump impeller are also made of steel stampings assembled by furnace brazing.

The cylinder head and water jacket are stamped from low-carbon steel sheet. Exhaust and intake ports are stamped in halves and joined by brazed lock seams. Tungsten-vanadium alloy valve seat inserts are pressed into the ports which are then assembled in the cylinder heads.

Cylinders and cam follower guides are made of SAE 4140 steel tubing. These and the remaining parts, 120 pieces in all, are assembled sufficiently to hold together in the brazing furnace. Crimping, rolling, press fits and resistance welding are used for this purpose.

During assembly, copper sheet, wire and paste are applied to the necessary points. The major subassemblies are sketched in Fig. 1.

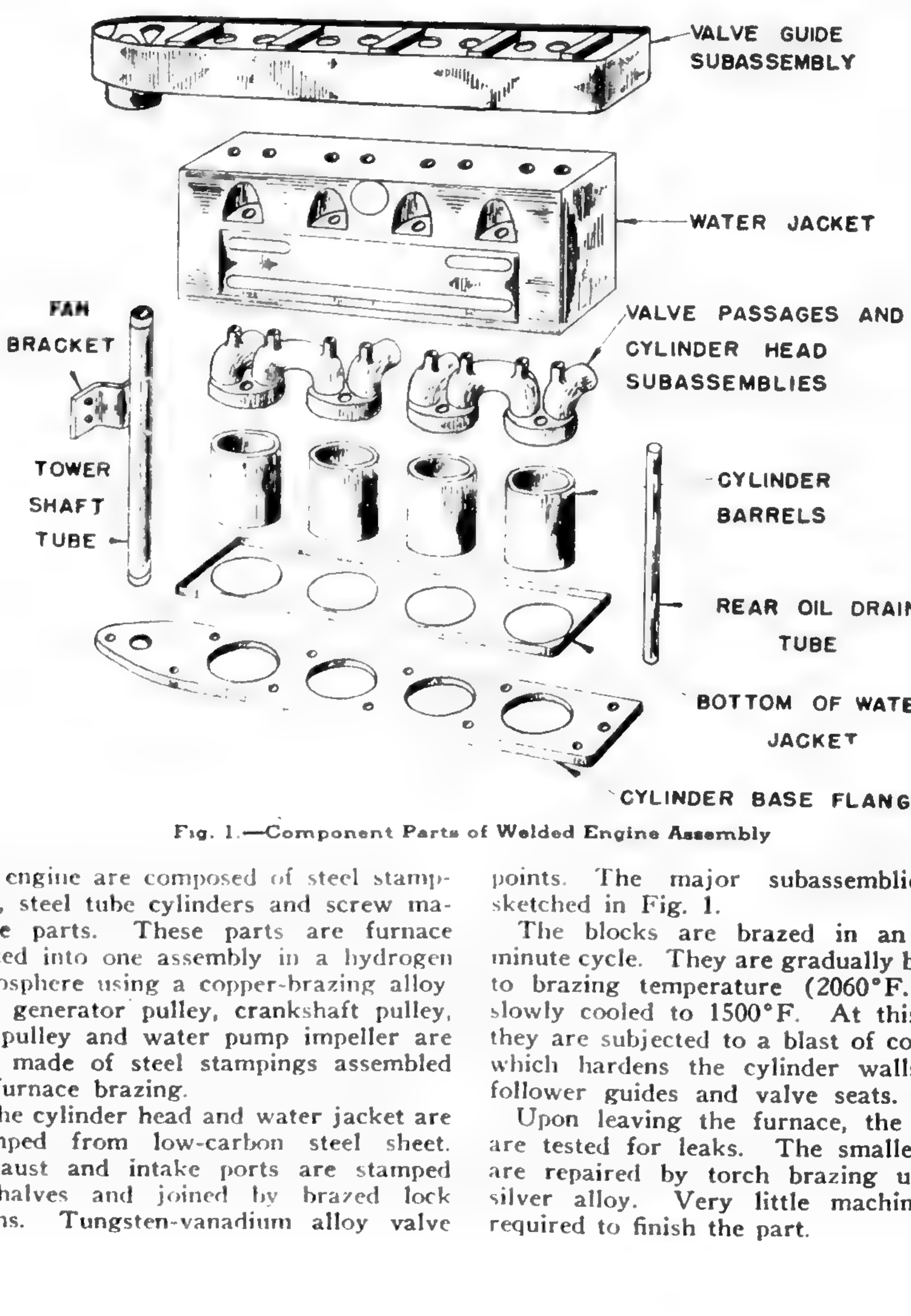


Fig. 1.—Component Parts of Welded Engine Assembly

The blocks are brazed in an eight-minute cycle. They are gradually brought to brazing temperature (2060°F.) then slowly cooled to 1500°F. At this time, they are subjected to a blast of cool gas, which hardens the cylinder walls, cam follower guides and valve seats.

Upon leaving the furnace, the blocks are tested for leaks. The smaller ones are repaired by torch brazing using a silver alloy. Very little machining is required to finish the part.

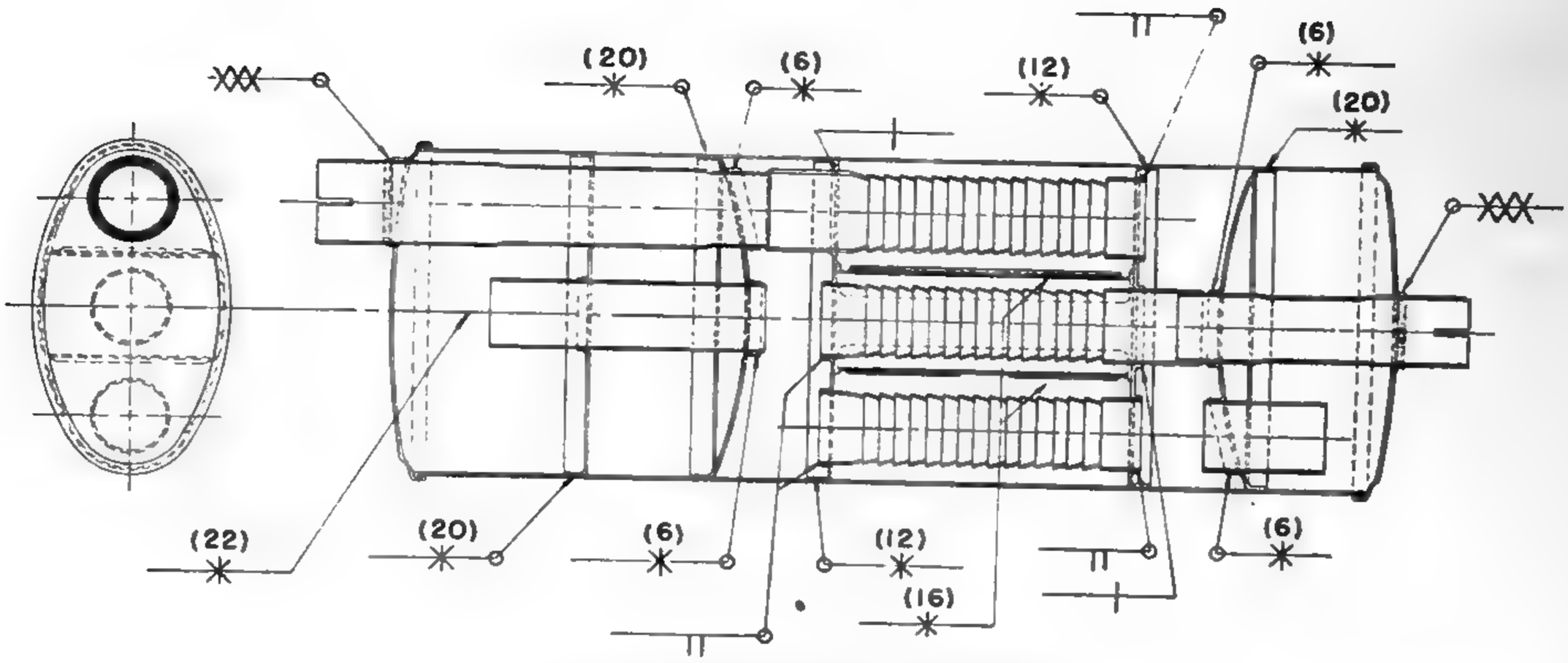


Fig. 2.—Welded Exhaust Muffler

Valve Mechanisms

Rocker arms, although usually made of forgings, are being welded in some instances. Fabrication involves the resistance welding and brazing of stampings and screw machine parts to form the complete rocker arms.

Tappets have a disc of abrasion-resistant material (for example, SAE 52100) on the bottom face, which rubs against the cam. This disc is projection welded using a ring-shaped embossment to the remainder of the tappet which is generally made as a screw machine part or a deep-drawn stamping.

Valves designed for heavy-duty service frequently have their seating surfaces improved by means of a hard-facing material. Still higher temperature service requires valves of the sodium-cooled type. Such valves are forged or machined hollow. The top cap or bottom of the stem contains a small hole in its center through which the proper amount of sodium is introduced. This hole is subsequently closed by resistance or arc welding.

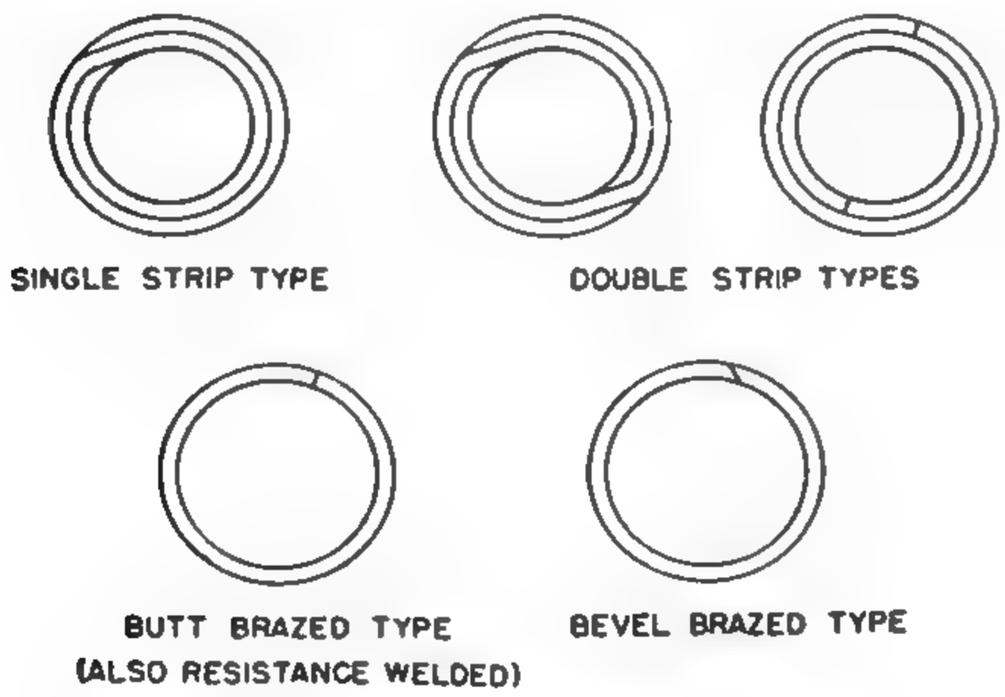


Fig. 3.—Automotive Steel Tubing

Radiators

The major joining process used for radiator fabrication is soft soldering, although some spot welding is used for securing various parts prior to soldering. In addition, spot welding is used to secure side supports and bolting strips.

Exhaust Systems

Exhaust and tail pipes are generally made of low-carbon steel strip. The strip is rolled into a tube and welded in one continuous operation. Gas and resistance welding tube mills are both used for this operation. The requirements are gas tightness and easy formability.

Exhaust mufflers are made of light-gage sheet parts rolled and stamped to shape. The side seams are usually spot or seam welded. End joints are rolled as well as seam welded. Baffle plates and other parts are spot welded. Aluminized sheet steel is used by some manufacturers for greater corrosion resistance on exhaust systems. Figure 2 shows a cross section of one type of muffler.

Fuel Lines

Considerable quantities of small size tubing are used in an engine for fuel, oil, hydraulic and vacuum lines. This tubing is of two types—single and double wrapped. (See Fig. 3.)

Double wrapped tubing is made by rolling one or two pieces of copper-plated strip and brazing it in a furnace in one continuous operation. The brazed joint extends around the full circumference and small voids are relatively unimportant.

The single wrapped or butt-brazed type, as the name implies, is rolled in a

single thickness and brazed in a butt joint. A void in the brazed joint is more serious, hence the rating is lower. However, with appropriate testing, single wrapped tubing can be used for all engine applications where the requirements are freedom from leaks and easy formability.

Oil Pans

The oil pan body consists basically of a deep-drawn stamping with several baffles and reinforcements spot and projection welded to it.

Where production requirements are relatively low, welding is performed by a large number of single-point rocker arm or press-type spot-welding machines. In such a case, the baffle stampings may be located by means of holes in the baffle flanges and embossments stamped in the pan body. The baffle is forced into position so that the hole snaps over the embossment, thus determining the correct location.

Where production requirements are high, oil pans are usually welded on high-speed, multiple-point machines. For some applications, a series of welding fixtures are built into a merry-go-round which automatically indexes successive pans into the welding machine. In other installations, a series of multiple-transformer type press welding machines may be placed in a straight line so that the pan passes from one machine to the other with a direct flow of material until completion.

Oil pan drain plug bosses are usually projection welded. Some are made of screw machine parts joined by projection welds using an annular embossment to the pan at a level low enough to permit good drainage. This boss is ordinarily located on the rear face to be safe from impact.

Still other bosses are stamped from flat sheet and are dome projection welded on the inside in a depression to obtain full drainage. The drain plug gasket seals against the outside surface of the pan. Impacts from road obstructions do not rupture this weld. Figure 4 illustrates such a boss and the riveted casting formerly used for the purpose.

Oil Filters

Oil filters are made of deep drawn stampings, screw machine fittings, etc. Some manufacturers use resistance welding entirely for joining the parts, whereas others furnace braze and weld, or braze alone.

Other Parts

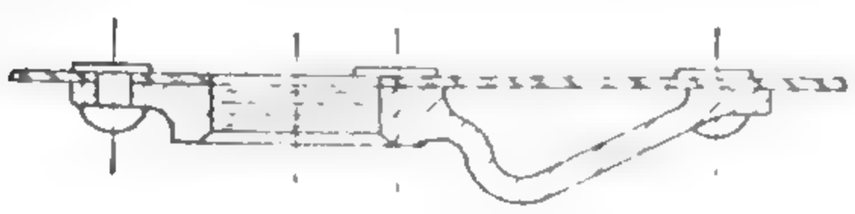
Other small engine components and accessories involve welding in some instances. Among these are air cleaners, filler pipes, crankcase ventilator pipes, crankshaft counterbalance weights, water distribution tubes, pulleys, water pump impellers, torsional vibration dampeners, brackets, mountings and throttle linkage.

CHASSIS APPLICATIONS

Frames

The development of welding on chassis frames has progressed from an all-riveted assembly, through the composite riveted and welded, to the all-welded frame. This change has been possible after studying the requirements and then correcting the design to permit proper application of welding.

Frames normally are composed of side members, cross members and, in some instances, center or *X* members, with other components such as brackets and reinforcements. The side member is usually reinforced with a plate or with a sub-side member to form a box section which may be flash welded, spot welded



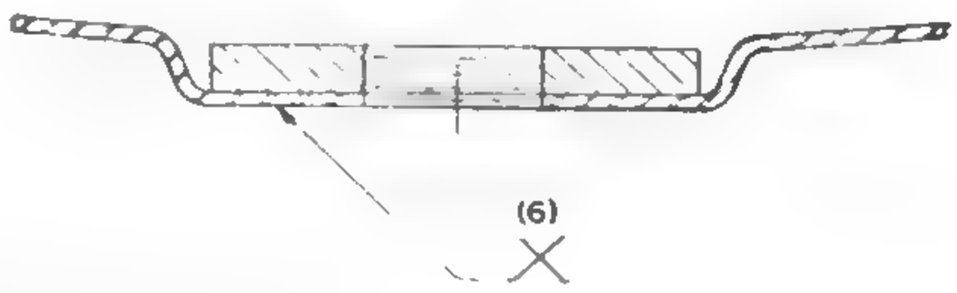


Fig. 4.—Oil Pan Drain Plug Bosses

Casting previously used—riveted in place and soft soldered to insure leak tightness.

Welded design—stamping projection welded in place. Depression in pan permits full drainage. Leak tightness insured by gasket of plug.

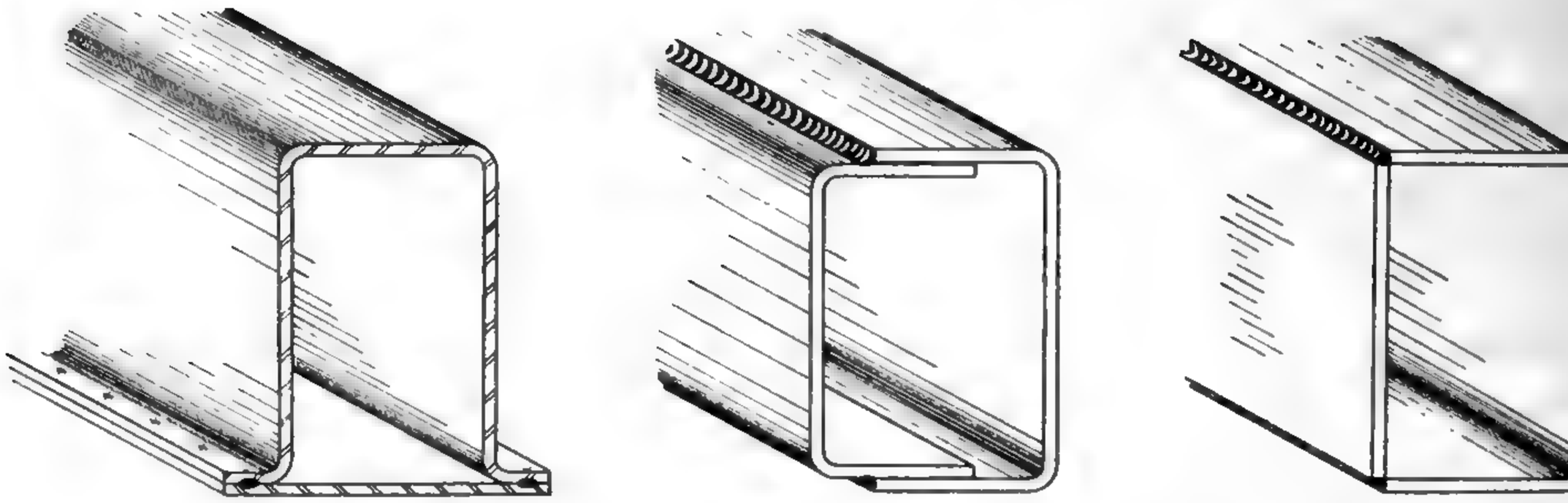


Fig. 5.—Typical Frame Side Members

or arc welded by either automatic or manual methods; unit cost usually is the deciding factor. Figure 5 shows three typical side member sections; a flanged *U* section with a reinforcing plate spot welded thereto, a normal box section with sub-side member arc welded into the side member and a U section with an arc-welded reinforcing plate forming one side of the box section. Any of these produces a satisfactory member, having considerable rigidity in torsion and bending.

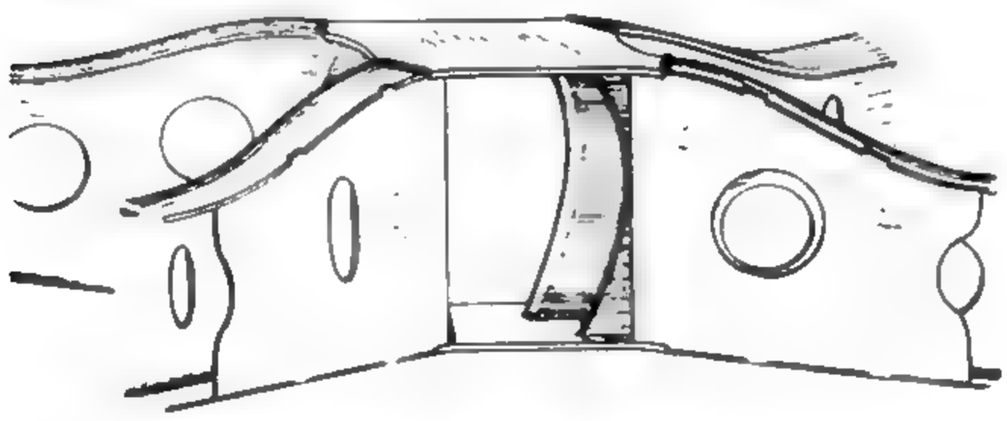


Fig. 6.—Arc-Welded X-Section Frame Member

A typical *X* or center section (Fig. 6) all welded by arc welding or flash welding is highly resistant to torsional or bending stresses.

Cross bars are frequently arc welded to the side members, usually by manual arc welding, using a fillet weld (Fig. 7), producing an assembly of high strength and rigidity.

Rear Axle Housings

Welding has made possible the present rear axle housing of pressed steel construction with its inherent strength and simplicity of design. The tubular sections used may be welded (Fig. 8) by automatic arc welding, flash welding or in a tube mill and cut to length, the bearing end of the tube being upset and the banjo end formed. Two halves are then flash welded to form an assembly ready for machining operations. Another method shown in Fig. 9 uses a developed blank to form a section of tube and banjo; the sections are welded together and the bearing ends upset. The use of either flash or arc welding produces a satisfactory assembly, the choice being determined by economic factors.

Fuel Tanks

The use of terne plate for fuel tanks is standard since it is corrosion resistant and readily welded by the seam welding process (Fig. 10) producing an economical and leakproof unit. Repairs may be made by gas welding.

Fixtures for high production can be used to make the welding operation fully automatic and with present welding controls, repairs can be held to a minimum.

Propeller Shafts

Propeller shafts are commonly made from welded tubing with the end forgings arc welded or flash welded in place (Fig. 11). Concentricity, balance at

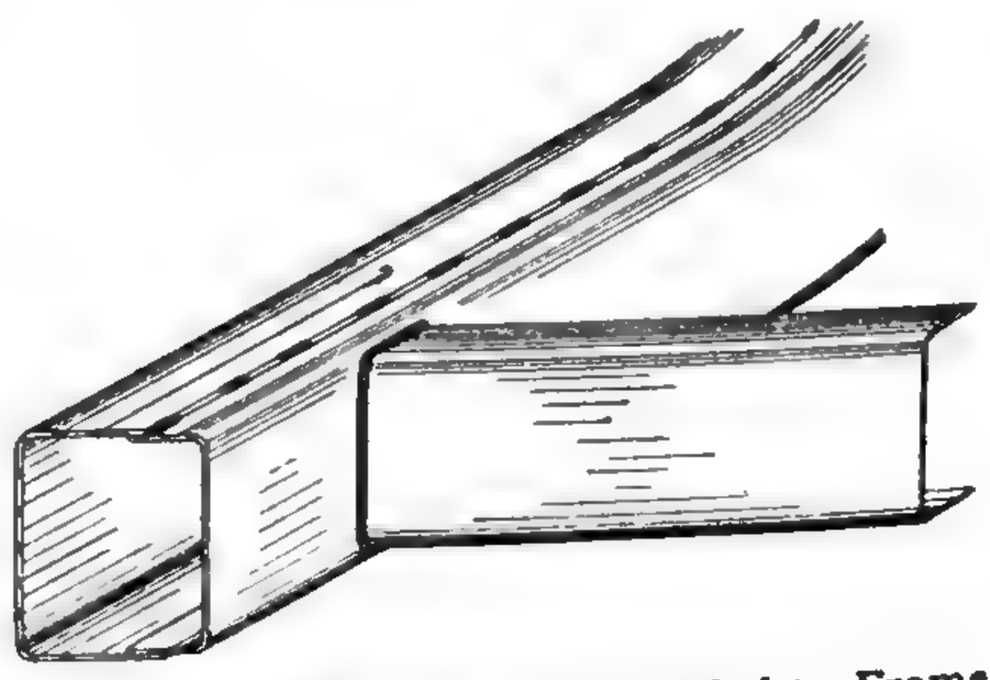


Fig. 7.—Cross Member Arc Welded to Frame Side Member

high speeds and high torque resistance are the prime requirements.

Wheels

Welding of wheel rims has remained standard in the industry over a period of years. Strip stock is rolled and flash welded into a hoop and, after the flash has been removed, expanded to size and formed to shape.

Wheel design has evolved from the artillery wheel, through the wire wheel and the welded spoke wheel to the present perforated disc spider which has been riveted to the rim. At present, replacement of the rivets with spot or projection welds is being studied

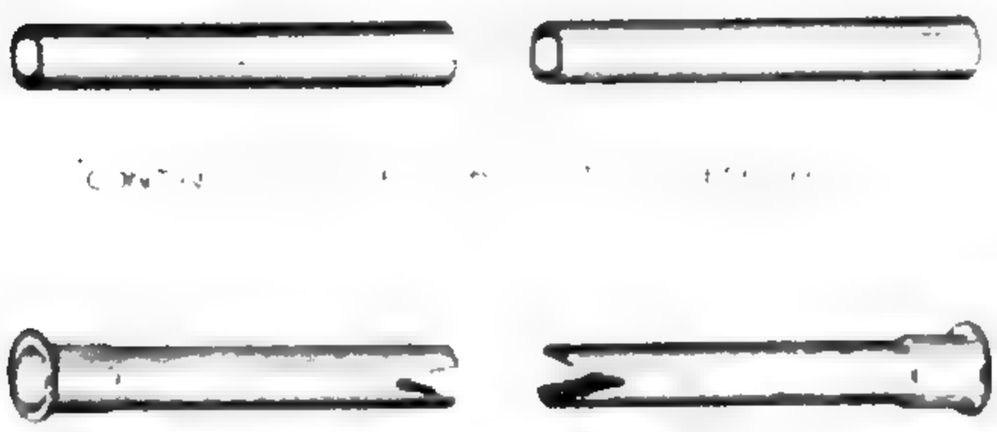


Fig. 8.—Welded Rear Axle Housing Made from Tubing

BODY APPLICATIONS

As indicated previously, extensive use is made of various welding processes in the fabrication and assembly of automotive bodies. Because of the extremely large number of welding operations that are used in body work, it is believed desirable to consider the types of applications by welding process used rather than to attempt a detailed discussion of the various operations. Further information on resistance welding equipment will be found in Chapter 15.

Spot Welding

Spot welding is by far the most widely used resistance-welding process in automotive body assembly. The general types of spot welding equipment and typical applications are as follows:

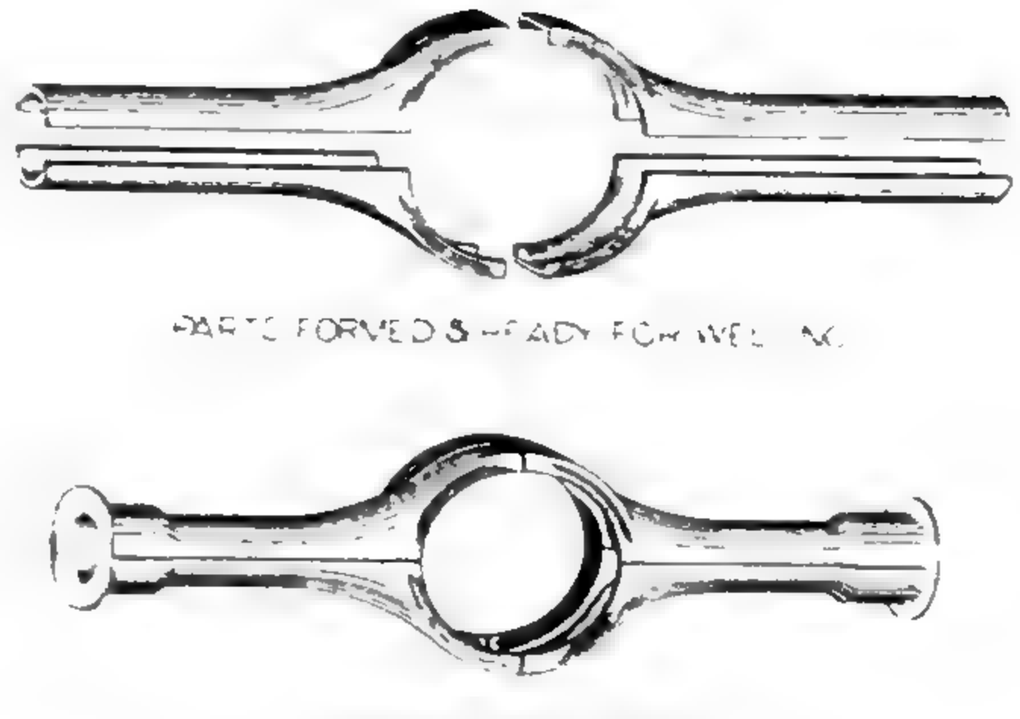


Fig. 9.—Welded Rear Axle Housing Made from Formed Blanks

Stationary Spot Welding Machines.—These machines are generally used for small assemblies which can be handled easily and which contain relatively few welds, or for miscellaneous low production runs which require the flexibility obtainable with this type of equipment.

Multiple Spot-Welding Machines.—Units of this type are generally used on high-production jobs where the increased production rates justify the additional capital expense. Figure 12 shows a multiple-spot machine which produces 172 spot welds simultaneously on an auto body subassembly. Large assemblies requiring 100 to 200 spots each are being

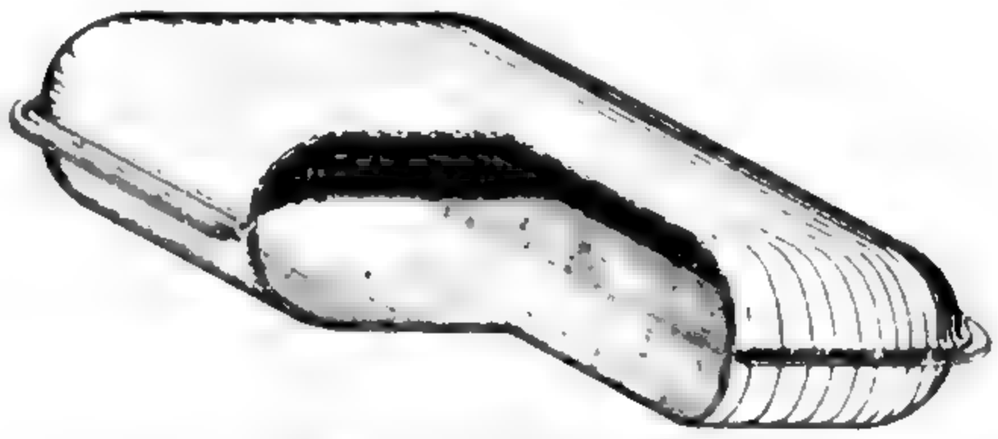


Fig. 10.—Seam-Welded Fuel Tank

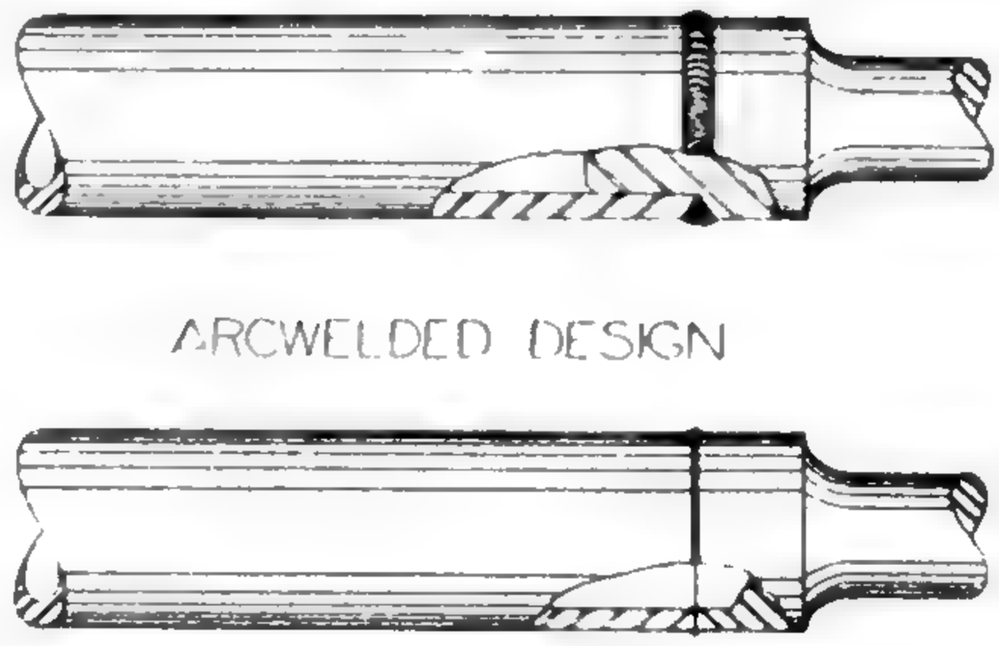


Fig. 11.—Welded Propeller Shafts

produced at rates up to 400 units per hour. Sometimes multiple-spot machines are set up in a progressive series of three or four machines, with automatic conveyor feeds between them. This permits high-speed production of complicated assemblies without creating undue maintenance or design problems on any one machine.

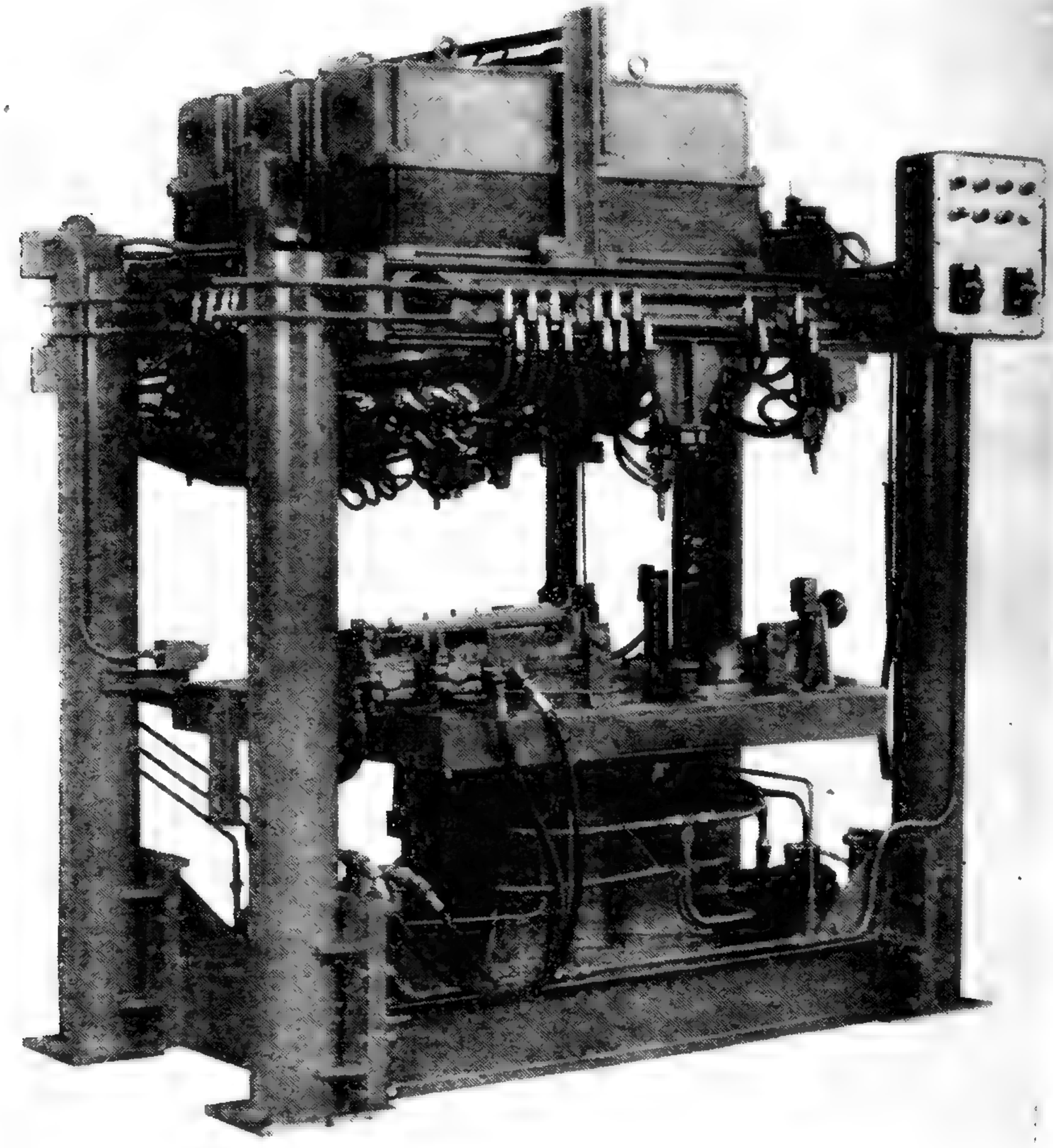


Fig. 12.—Typical Multiple-Spot Welding Machine

Many multiple-spot machines are designed with interchangeable electrode units so that the same *welding press* may be used for welding similar assemblies for different car models.

Several welding transformers are used to obtain flexibility, each welding transformer usually containing from one to four separate secondary windings. The transformers may be energized separately in sequence, in group sequence or simultaneously, depending upon production requirements and the power supply available. Three typical secondary circuit arrangements are shown in Fig. 13.

Portable Guns.—Much subassembly spot welding and all final assembly spot welding is done with portable welding guns (Fig. 14). These guns come in a large variety of sizes and shapes, the throat area varying from 4 sq. in. to approximately 800 square inches. Weld-

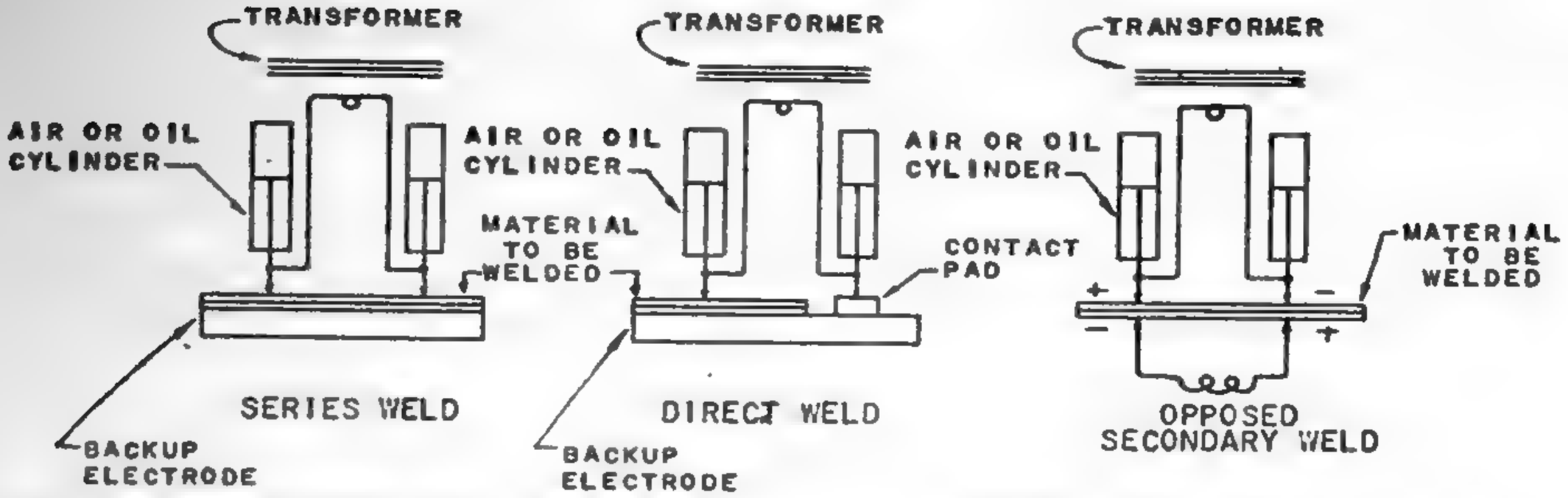


Fig. 13.—Typical Secondary Circuit Arrangements for Multiple-Spot Welding Machines

ing pressure is obtained from either an oil- or air-actuated cylinder. For normal operation, current is supplied to the guns by means of water-cooled secondary cables. Wherever possible, particularly on the larger guns, a counterweight or commercial balancer suspension is used to facilitate the gun operations. High-production guns are usually sequenced with a NEMA Type 3B timing device.

Projection Welding

A number of subassemblies are projection welded, particularly small items with closely spaced welds or heavier gage materials neither of which are too well suited to the multiple-spot welding. Figure 15 shows a projection-welded body floor reinforcement of material 0.080 to 0.100 in. thick.

Flash Welding

Flash welding is frequently used for butt joints in sheet metal panels where the weld line is of a reasonably simple contour. Complicated contours produce unduly difficult electrode maintenance problems which tend to offset many of the advantages of the flash-welding process. Typical body flash welds are shown in Fig. 16. To obtain the required metal finish on exposed body panel surfaces requires very accurate electrode alignment.

Gas Welding

A considerable amount of gas welding is used in automotive body construction, particularly where poor fitup in butt joints requires the addition of an appreciable amount of filler material. On exposed surfaces these joints are subsequently hammered below the finished body surface, cleaned, filled with solder and finished to smooth contours. This type of construction requires solder filling and high metal finishing costs. The holding fixtures are generally of a high-production type using water-cooled clamps to maintain joint alignment and restrict heat travel into the assembly. Loss of body contours and critical dimensional stability are among the major difficulties encountered in the gas welding of sheet metal assemblies. Typical gas welded joints are shown in Fig. 16.

Brazing

A limited amount of brazing is performed where the reduced distortion due to the lower heat requirements is of sufficient importance to offset the addi-

Fig. 14.—Typical Portable Gun Welding Application

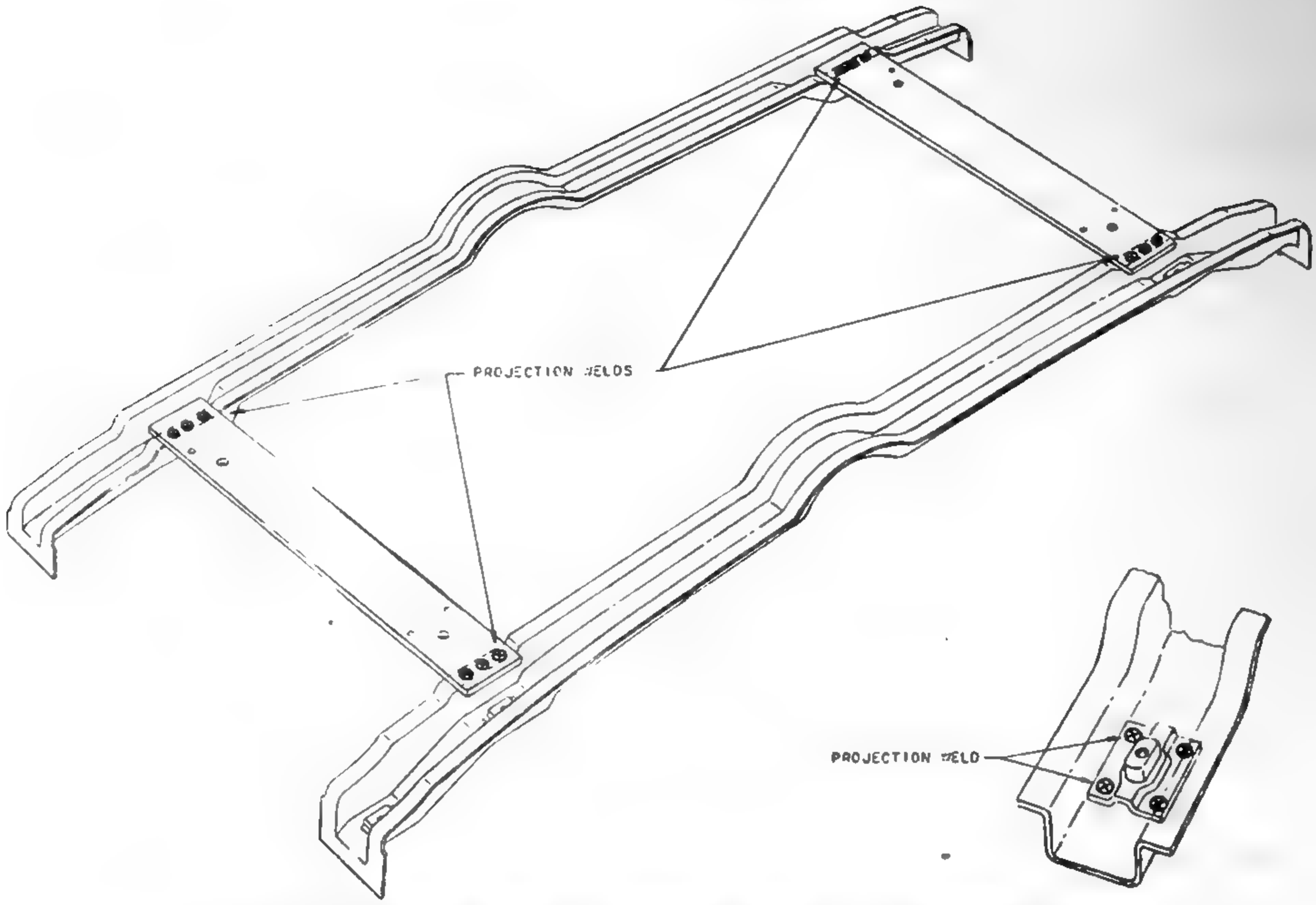


Fig. 15.—Typical Projection-Welded Body Floor Reinforcement

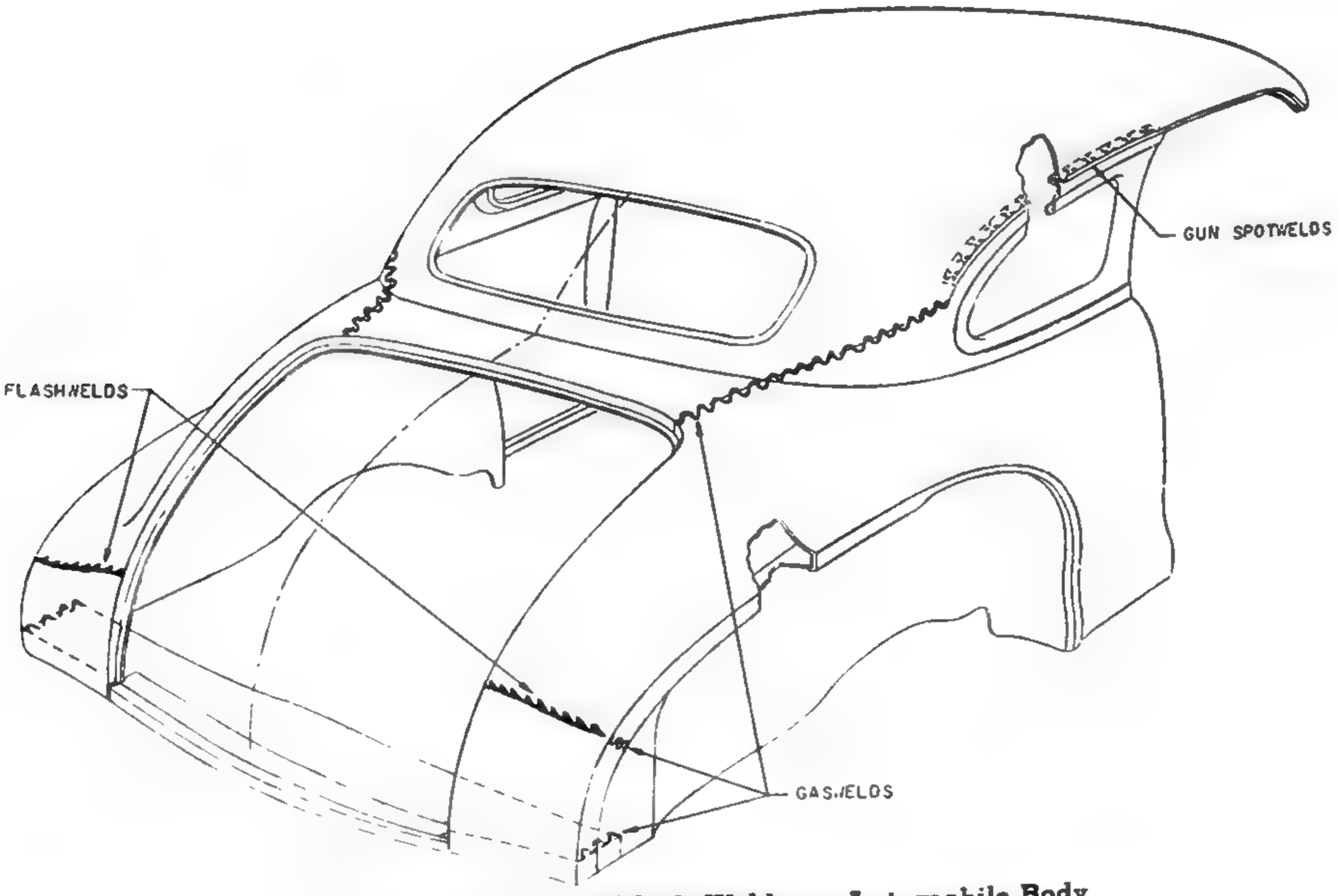


Fig. 16.—Spot, Gas and Flash Welds on Automobile Body

tional material cost. On finished surfaces brazed joints sometimes cause difficulty due to *season cracking* and *mapping* through the painted surfaces.

Arc Welding

A considerable amount of both a.c. and d.c. arc welding of sheet metal is being performed, particularly for attaching reinforcing members or at locations inaccessible to spot-welding guns such as unexposed body sections (Fig. 17). Low-penetration, high-deposit welding electrodes with very stable arc characteristics show appreciable merit in these applications. Alternating-current machines are rapidly becoming popular in automotive body shops, particularly due to their reduced operating and maintenance costs.

Cast-iron brackets are manually welded to the frame using pure nickel electrodes.

Miscellaneous Electrical Parts

A number of resistance-brazing and spot-welding applications are performed in joining terminals to ends of wires and joining two or more wire sections together. There are a number of hot upsetting applications used in fabricating small parts for electrical use. This involves the use of a regular spot-welding machine for upsetting rivets, studs and metal prongs. Alloy-faced tips are generally used for this application due to the extreme wear condition involved. (See Chapter *22* for information on resistance brazing.)

There are a number of applications of spot welding and projection welding of mild steel brackets to housings such as switch cases, horn assemblies, etc.

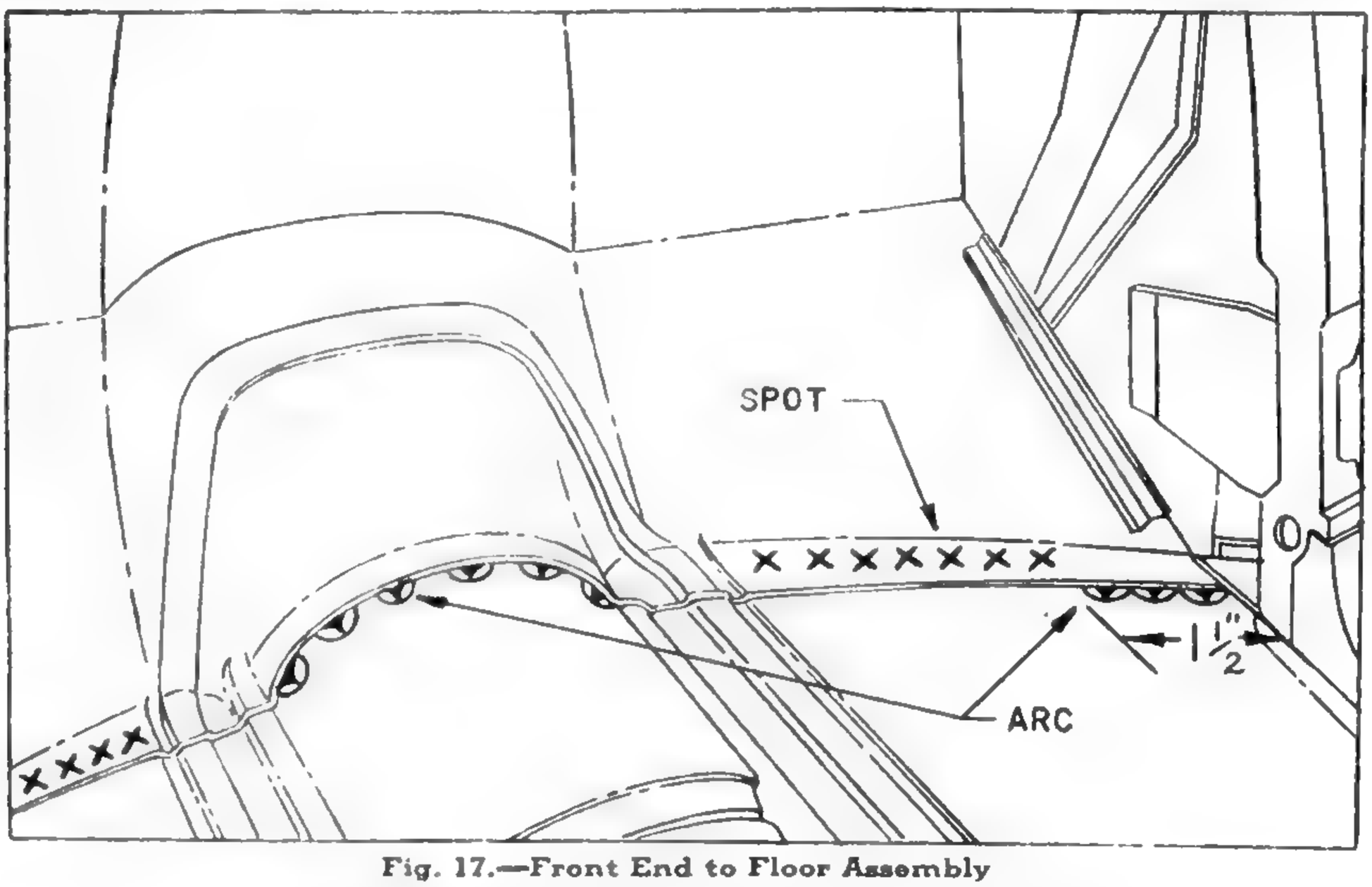


Fig. 17.—Front End to Floor Assembly

Arc welds used in locations inaccessible for spot welding.

MISCELLANEOUS APPLICATIONS

Starter Motor and Generator Frames

These assemblies are made up by rolling flat sheet into cylindrical forms and arc welding the seam. Small frames are generally welded by use of the automatic carbon arc. The heavier frames are welded by submerged arc welding. Manual arc welding is used for repair of frames and for welding laminated pole shoes.

APPLICATIONS ON SPECIAL VEHICLES

Commercial Busses and Coaches

Many of the items being fabricated on coaches and busses are similar to those currently being used for passenger automobiles as previously described. However, since the production requirements of this type of vehicle are drastically lower

than those of passenger cars, it is impossible to purchase special-purpose equipment for the assemblies as would be done in other automotive plants. Therefore, the spot-, seam- and arc-welding fixtures and equipment in bus plants are usually much simpler and more adaptable to change than those in automobile plants.

Aside from the types of equipment involved, the design of the parts is similar to that in automobiles with the possible exception that in bus manufacture it is expected that the operating factor of the vehicle will be much higher and, therefore, the construction is correspondingly more rugged. Since most coach models are considerably heavier than automobiles, it is necessary that the parts be heavier and, therefore, the welding equipment involved is generally designed to handle greater thicknesses of material. On most coach models the following assemblies are welded making use of the processes indicated:

Jack-knife doors—Spot welding
Driver's toe board—Seam welding
Side posts—Projection welding
Window panels—Spot welding
Doors—Spot welding
Stepwell—Spot welding
Fuel tanks and surge tanks—Spot and seam welding
Fan pulley—Spot welding
Seat frames—Brazing

Trucks

The welding operations and equipment for the manufacture of motor trucks are, in most instances, similar to those which are employed on passenger automobiles. As in the case of commercial busses and coaches, the production of trucks is lower than that of automobiles and, therefore, it is sometimes impractical to provide the extensive tooling that is normally used for passenger-car manufacture. Generally speaking, the assemblies on trucks, cabs and frames are also heavier than those of automobiles, which necessitates heavier equipment. Also, it is usually not feasible to have as many special-purpose machines for truck parts and, therefore, more general use is made of standard types of machines than in automobile fabricating plants.

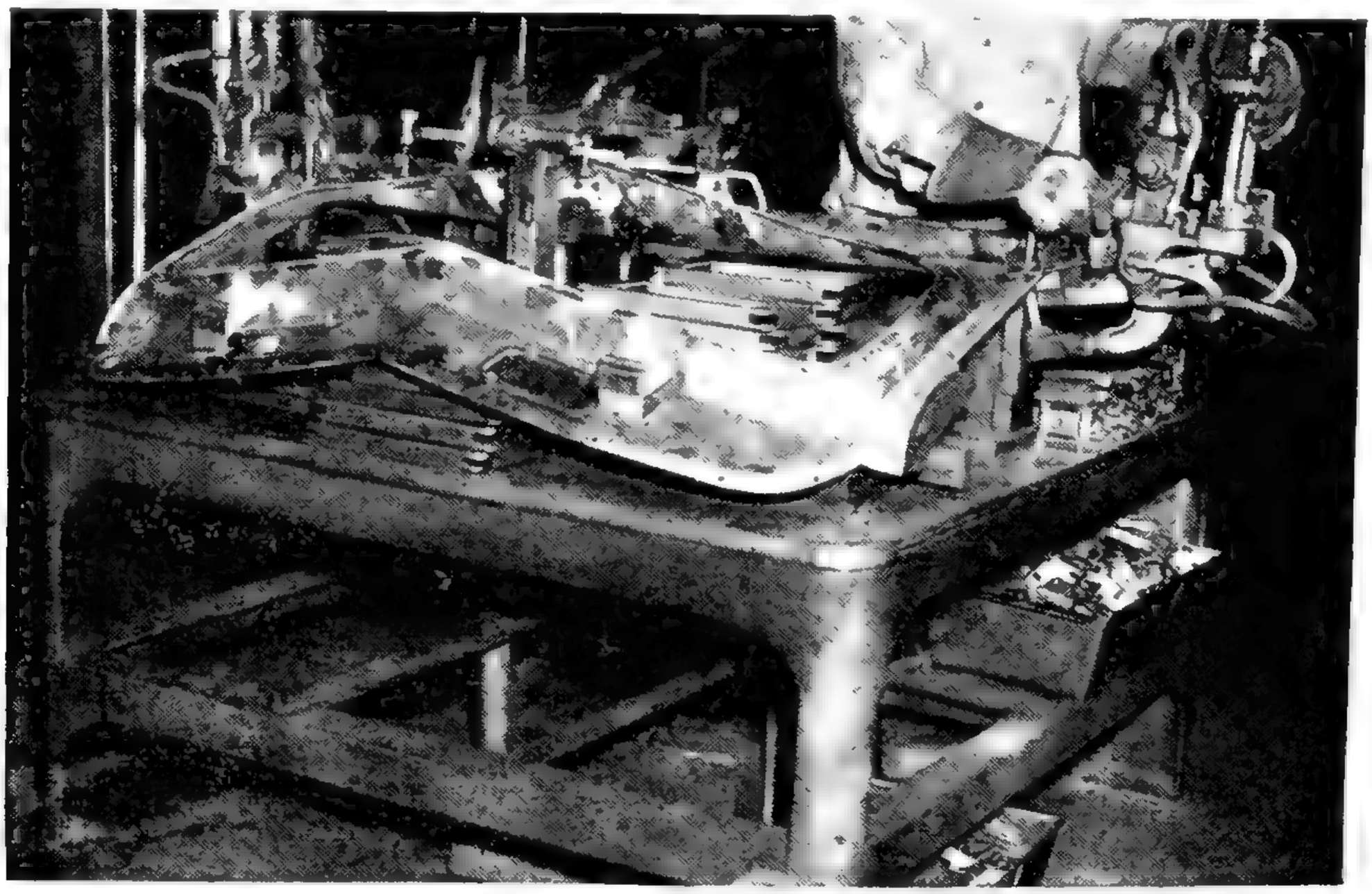


Fig. 18.—Welding Truck Cab Assembly with Portable Gun

In the case of cab assemblies for lighter trucks where the production is relatively high, the equipment is very similar to that employed on automobiles, and the operations follow approximately the same procedure. This includes the use of multiple-electrode spot welding machines for door, cowl, roof and back assemblies, portable guns for cab assemblies (see Fig. 18) and a certain amount of arc and

gas welding where it is impractical to use resistance welding.

The fuel tanks used on the smaller trucks are very similar to those used in automobiles, in that they are composed of terne-plated material and seam welded to form a gas-tight container. Gasoline tanks on some of the heavier models are extremely large and designed so that they do not lend themselves to seam welding, and a certain amount of arc and gas welding is employed (see Fig. 19).

The frames of trucks are primarily riveted assemblies, although recently steps have been taken toward spot- and arc-welded construction wherever possible. The welding operations involved in accessory items such as generators, starter motors, etc., are essentially the same as those used in general automobile practice.

Trailers

The problems involved in the manufacture of trailers for highway use are somewhat different from those encountered in general automotive practice. This is due not only to the size of the elements involved, but also to the fact that the production of these trailers is very low.

Recently, enclosed trailers have been made by replacing sheet steel with aluminum and stainless steel in an effort not only to improve their appearance but to provide a certain amount of corrosion resistance as well, inasmuch as many of these trailers are exposed to the weather continuously.

While most of the trailers being manufactured today are basically of welded construction, the methods used are not as elaborate as those used on automobile bodies due to the lower production involved. However, the primary structure is arc welded, and spot welding is utilized on thinner sheets wherever practical.

Hydraulic brake and wheel assemblies are also arc welded similar to those which are found on the general types of motor trucks. There are a few special-purpose resistance welding machines being utilized for connecting the sheet sides to the structure of the trailer. Most of the resistance welding done, however, is handled with standard machines of either the portable or the pedestal type. Some manufacturers of trailers also utilize flash welding on assemblies which readily lend themselves to this type of fabrication. However, specialized applications of flash welding have not generally been used due to the low production which prohibits too high an expense in equipment.

Tractors

In the manufacture of farm tractors, the use of welding has become more and more important. The processes being used include spot welding, seam welding, projection welding and flash welding, as well as gas and arc welding. In certain instances special machines for resistance-welded assemblies are justified, although in general, standard equipment is being used since the production of these tractors does not warrant large expenditures for highly specialized equipment.

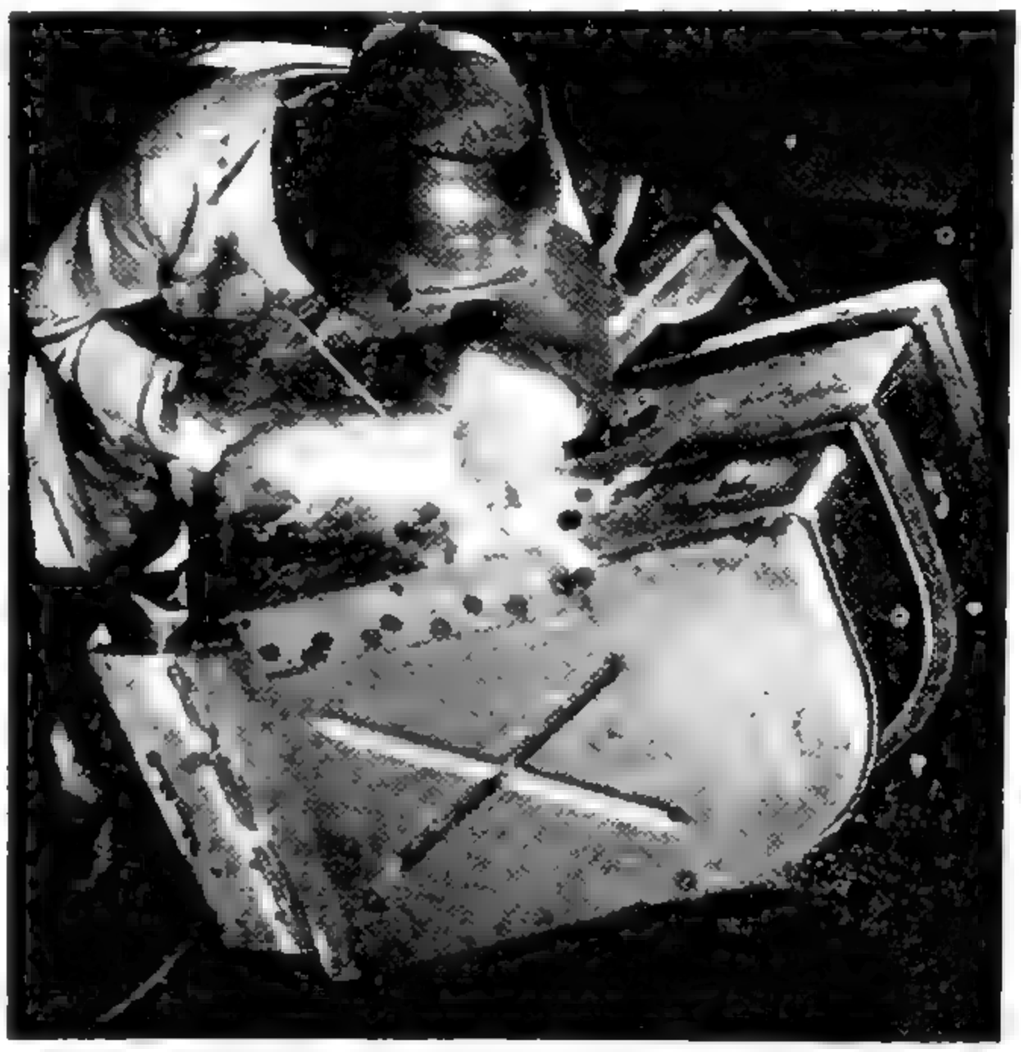


Fig. 19.—Arc Welding Truck Gasoline Tank

Fuel tanks for farm-type tractors are generally seam welded in a manner similar to that used in automobiles, with the exception that the shape of the tank is often altered to suit the lines of the tractor since the tank is completely exposed to view (see Fig. 20). In typical farm tractors, the transmission and differential housing are of cast iron. The framework of the tractor, steering mechanism and miscellaneous items such as hoods, grilles and cowl assemblies are fabricated by welding. Heavier parts, such as the frame and drawbar assemblies, are generally arc welded and the sheet metal parts spot welded, using either

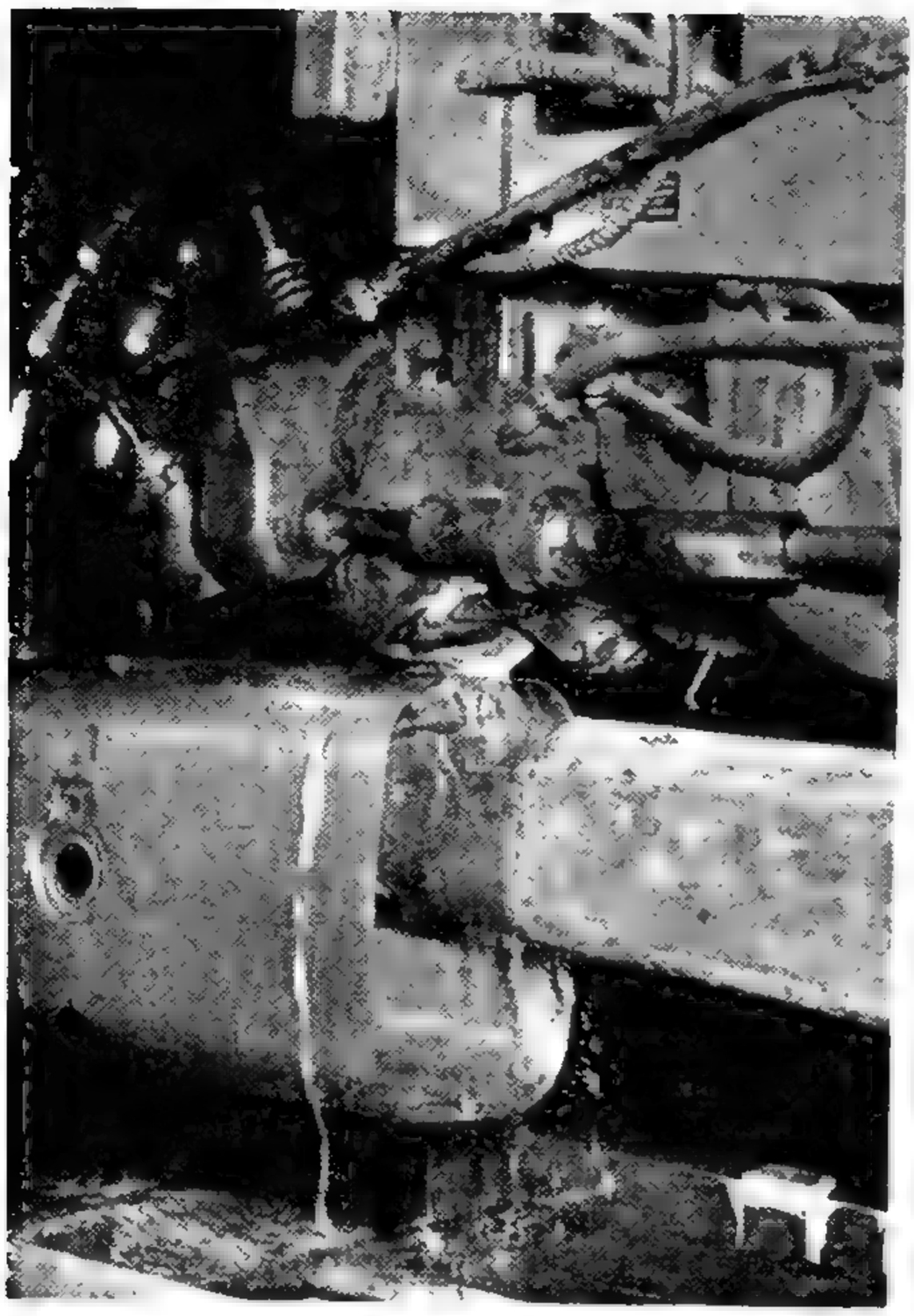


Fig. 20.—Seam Welding Gasoline Tank for Tractor

portable or pedestal type machines or, in the case of some high-production items, special-purpose multiple-electrode machines. Many of the round shafts employed in the various assemblies of the tractors are flash welded to forged parts such as universal joints or worm gears. In the manufacture of tractors, there are also many small assemblies which are brazed using torches, furnaces or induction coils for heating. The materials used for this brazing depend upon the details of the assembly, but most of the common materials are employed.

Manufacturers of heavy, crawler-type tractors, which are commonly used for road work, employ welding operations which are radically different. The assemblies used in crawler tractors are subjected to very severe service and, inasmuch as the loads are heavier, it is necessary to have extremely large parts to avoid breakage. Arc welding is usually used and automatic arc-welding procedures are employed wherever applicable. In some of the heavy, crawler-type tractors, the transmission and differential housings are completely fabricated rather than being cast (see Fig. 21). This involves a large amount of welding on plates ranging from $^1/_2$ to $1^1/_2$-in. thick. Also, the tractor frames on crawler-type tractors are normally of arc-welded construction. In most cases, these are completely machined after fabrication. Most of the arc welding is done in special positioning fixtures rather than on full positioners, inasmuch as it is often necessary to only rotate the parts in one plane. It is common to tack weld the component parts of these large assemblies in a locating fixture which is not capable of positioning, and then reload the assembly in positioning fixtures for final welding. Due to the size of many of these assemblies, it is often possible to break them down into smaller component assemblies in order to simplify the operations and eliminate the necessity of positioning the entire assembly for a large portion of the welding.

Fig. 21.—Fabrication of Heavy Tractor Drive Housing

BIBLIOGRAPHY

1. *Brief History of Budd All-Steel Body,* J. W. Meadowcroft, The Welding Journal, September 1938.

2. *Arc Welding in Automotive Industry,* H. D. Doud, Industry and Welding, October 1938.

3. *Welded Construction,* Automobile Engineer, October 1938.

4. *Use of Electric Resistance Welding in Automobile Industry,* A. Di Guilio, The Welding Journal, November 1938.

5. *Manufacture of Rear Axle Housings,* E. L. Bailey and V. Knecht, The Welding Journal, January 1939.

6. *Automatic Carbon Arc Welding in Automotive Industry,* F. M. Maichle, The Welding Journal, March 1939.

7. *Spot Welding of Automobile Grade Mild Steel,* W. F. Hess and R. A. Wyant, The Welding Engineer, December 1939.

8. *Welding Propeller Shaft Tubing for Automotive Industry,* G. C. Gridley, The Welding Journal, March 1940.

9. *Welded Axle Housings,* J. W. Meadowcroft, Steel, April 27, 1940.

10. *Multiple Series Press Welding,* J. Gilbert, Tool Engineer, August 8, 1941.

11. *Automotive Welding,* S. M. Spice, V. Fegley and L. M. Skidmore, The Welding Journal, November 1941.

12. *Light Welding,* Automobile Engineer, October 1945.

13. *Fabricating and Heat Treating Push Rods at Ford Rouge Plant,* Industrial Heating, January 1, 1946.

14. *Silver Alloys Brazed Auto Parts,* A. Bregman, American Machinist, January 31, 1946.

15. *Welding Speeds Frame Production,* Industry and Welding, September 1946.

16. *Modern Trends in Body Assembly and Welding,* L. M. Benkert, Automotive and Aviation Industries, December 1, 1946.

17. *Spot Welding Mass-Produces Body Panels for Kaiser-Fraser Car,* American Machinist, August 1947.

18. *Automotive Chassis Welding,* O. E. Heitman, Steel, December 4, 1949.

19. *Recommended Practices for Salvaging Automotive Gray Iron Castings by Welding,* American Welding Society, 1950.

CHAPTER 55

AIRCRAFT*

INTRODUCTION

WELDING IN AIRCRAFT has now found extensive use in both primary structural and non-structural applications. Choice of material is dictated principally by design requirements, although weldability is also a factor, and the welding process is then selected on the basis of applicability to the material selected, the quantity to be produced, the cost of the process and the structural efficiency of the joint produced.

A very wide variety of materials and designs are required in aircraft fabrication, resulting in the use of most of the welding processes. Because the materials used include aluminum and magnesium alloys, low-alloy steels, austenitic steels and high-nickel alloys, a wide variation of techniques for most of these processes is also encountered.

MATERIALS

In the following tables an effort has been made to include as many of the alloys commonly used in aircraft as possible, together with an evaluation of the weldability of each.

Although the details of the various welding processes, compositions of materials used and the general welding procedures are covered in detail in other chapters, a summary of materials and applicable processes for aircraft fabrication is shown in Tables 1 through 6.

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DESIGN

Arc and Gas Welding

Structural Joints in Low-Alloy Steels.— Assemblies made from low-alloy steels by arc and gas welding include such structures as engine mounts and landing gears. (Some use is still being made of welded tubular fuselage structure.) It is not considered good practice to converge more than six tubular members into a single cluster. An unreinforced butt design previously was not generally acceptable for a structural joint, but is now coming into use. Adequacy of design is generally demonstrated by static, impact and fatigue tests.

The methods for computing the design loads for welded joints in structures are given in Specification ANC-5, *Strength of Metal Aircraft Elements*†, and a detailed discussion will not be presented here. In some cases welding is considered in ANC-5 to reduce the strength of the metal near the weld to a value of 80% of base metal strength. In other cases no reduction is required and in still other cases intermediate strength reductions are specified.

In connection with the strength considerations of structural joints, thought must be given to the elimination of stress concentrations by adequate distribution of the loads. This may be accomplished through the use of various types of reinforcements such as wrap plates and gussets which must be designed to permit high quality welding. A poor weld at a point already subjected to stress concentrations might result in the premature failure of the assembly. One of the points to be considered is the relative masses of the details being welded so that adequate penetration of the weld bead into each is assured and overheating is avoided.

† See Bibliography.

Table 1—Aluminum and Aluminum Alloys[a]

Applications: General Airframe Structure, Cowling, Fairing, Air Ducts, Tanks and Furniture

Description	Strength[b] Hard Ult.	Hard Yield	Soft Ult.	Soft Yield	Specification	Spot and Seam Welding[c]	Flash Welding	Arc Welding: Inert Gas	Arc Welding: Shielded Metal	Gas Welding	Brazing: Torch	Brazing: Furnace and Dip
Clad plate, sheet, strip												
AL-75C2 5.6 Zn, 2.5 Mg, 1.6 Cu	73	63	33		AN-A-10	Good		Not used		Not used	Not used	Not used
AL-24C2 4.5 Cu, 1.5 Mg, 0.6 Mn	64	43	30		AN-A-13	Good		Not used		Not used	Not used	Not used
R-301 4.5 Cu, 1.0 Si, 0.9 Mn, 0.5 Mg	65	58	28		AN-A-22	Good		Not used		Not used	Not used	Not used
Plate, sheet, strip												
AL-75 5.6 Zn, 2.5 Mg, 1.6 Cu	78	67	35		AN-A-9	Good		Not used		Not used	Not used	Not used
AL-61 1.0 Mg, 0.6 Si, 0.25 Cu, 0.25 Cr	45	39	18	8	FED. QQ-A-327	Good		Good		Fair	Fair	Good
AL-52 2.5 Mg, 0.25 Cr	41	36	29	14	FED. QQ-A-318	Fair		Good		Fair	Fair	Fair
AL-24 4.5 Cu, 1.5 Mg, 0.6 Mn	68	46	26	10	AN-A-12	Good		Not used		Not used	Not used	Not used
AL-3 1.2 Mn	29	25	16	6	FED. QQ-A-359	Fair		Good		Good	Good	Good
AL-2 Commercially pure	24	21	13	5	FED. QQ-A-561	Fair		Good		Good	Good	Good
Extruded shapes, bars, rod												
AL-75 5.6 Zn, 2.5 Mg, 1.6 Cu	80	73	35	.	AN-A-11	Good		Not used		Not used	Not used	Not used
AL-24 4.5 Cu, 1.5 Mg, 0.6 Mn	68	46	26	10	FED. QQ-A-354	Good		Not used		Not used	Not used	Not used
AL-17 4.0 Cu, 0.5 Mg, 0.5 Mn	62	40	26	10	FED. QQ-A-351	Good		Not used		Not used	Not used	Not used
AL-14 4.4 Cu, 0.8 Si, 0.8 Mn, 0.4 Mg	70	55	35		AN-A-8	Good		Not used		Not used	Not used	Not used
Castings												
AL-356 7.0 Si, 0.3 Mg (Perm mold, Sand)	40	24	32	18	AN-A-34	Fair[d]		Good		Good	Good	Good
	32	22	28	16	AN-A-39	Fair[d]		Good		Good	Good	Good
AL-355 5.0 Si, 1.3 Cu, 0.5 Mg (Perm mold, Sand)	43	26	30	21	AN-A-41	Fair[d]		Good		Good	Good	Good
	35	25	28	23	AN-A-40	Fair[d]		Good		Good	Good	Good
AL-195 4.5 Cu (Sand)	40	31	31	16	AN-A-35	Fair[d]		Not used		Not used	Good	Good
AL-43 5.0 Si (Perm mold, Sand)	24	9	.	.	FED. QQ-A-596	Fair[d]		Good		Good	Good	Good
	19	9	.	.	AN-A-27	Fair[d]		Good		Good	Good	Good
AL-13 12.0 Si (Die)	33	18	.	.	AN-A-38	Fair[d]		Good		Good	Good	Good
Tubing												
AL-61 1.0 Mg, 0.6 Si, 0.25 Cu, 0.25 Cr	45	39	18	8	WW-T-789	Fair[e]		Good		Fair	Fair	Good
AL-53 1.3 Mg, 0.7 Si, 0.25 Cr	39	33	16	7	WW-T-790	Fair[e]		Good		Fair	Fair	Fair
AL-52 2.5 Mg, 0.25 Cr	41	36	29	14	WW-T-787	Fair[e]		Good		Fair	Fair	Fair
AL-24 4.5 Cu, 1.5 Mg, 0.6 Mn	68	46	26	10	WW-T-785	Fair[e]		Not used		Not used	Not used	Not used
AL-3 1.2 Mn	29	25	16	6	WW-T-788	Fair[e]		Good		Good	Good	Good
AL-2 Commercially pure	24	21	13	5	WW-T-783	Fair[e]		Good		Good	Good	Good
HANDBOOK Reference Chapters for Processes	..	..	..	..	..	16	17	12	10	5	22	22

Limited experimental use, possible general use later

Applicable for alloys weldable by gas, but not generally used

[a] Refer to Chapter 32 for detailed discussion on welding of aluminum.

[b] Typical values, given in 1000 psi.

[c] Proper surface preparation and proper welding equipment are mandatory for satisfactory welds. Because of the possibility of corrosion, restrictions have been placed on the spot welding of bare 75S, 24S and 14S alloys in combination with themselves or each other (see AN-W-30).

[d] Limited use in thin sections with smooth surfaces.

[e] Poor accessibility and fit-up restrict the use of tubular forms. (See Section on Design.)

Table 2—Magnesium Alloys[a]

Applications: Limited Airframe Structure and General Non-Structural Assemblies such as Intake Ducts, Low-Pressure Tanks and Interior Furnishings. Used for Lightness and Rigidity

Description			Strength[b]				Specification	Spot and Seam Welding[c]	Flash Welding	Arc Welding		Gas Welding	Brazing
			Hard		Soft								
Dow No.	AMC No.		Ult.	Yield	Ult.	Yield				Inert Gas	Shielded Metal		
Plate, sheet, strip													
M	3S	1.5 Mn	36	27	32	17	AN-M-30	Fair	Not generally used	Fair	Not generally used	Good	Not used
FS-1	52S	3.0 Al, 1.0 Zn, 0.2 Mn	46	34	38	25	AN-M-29	Good		Fair		Fair	
Bar, rod, shapes													
J-1	57S	6.5 Al, 0.8 Zn, 0.2 Mn	44	31.5	..	..	AN-M-24	Not used		Good		Difficult	
M	3S	1.5 Mn	37.5	28	..	..	AN-M-26	Not used		Fair		Good	
FS-1	52S	3.0 Al, 1.0 Zn, 0.2 Mn	39.5	29	..	..	AN-M-27	Fair		Fair		Fair	
Castings													
H	265	6.0 Al, 3.0 Zn, 0.2 Mn	36	18	27	11	AN-M-36	Not used		Good		Not used	
M	403	1.5 Mn	14	4	..	..	AN-M-36	Not used		Fair		Not used	
C	260	9.0 Al, 2.0 Zn, 0.2 Mn	38	20	23	14	AAF-11349	Not used		Fair		Not used	
Tubing													
J-1	57S	6.5 Al, 0.8 Zn, 0.2 Mn	40	19	..	..	AN-T-71	Good[d]		Good		Difficult	
M	3S	1.5 Mn	35	14	..	..	AN-T-73	Difficult[d]		Fair		Good	
FS-1	52S	3.0 Al, 1.0 Zn, 0.2 Mn	35	16	..	..	AN-T-72	Fair[d]		Fair		Fair	
HANDBOOK Reference Chapters for Processes			..	..	..	..	..	16	17	12	10	5	22

[a] Refer to Chapter 33 for detailed discussion on welding of magnesium.
[b] Typical values, given in 1000 psi.
[c] Proper surface preparation and proper welding equipment are mandatory for satisfactory welds.
[d] Poor accessibility and fit-up restrict the use of tubular forms. (See Section on Design.)

Table 3—Chromium-Nickel Steels and Nickel Alloys

Applications: Corrosion Resistance and Heat Resistance—Exhaust Stacks, Fire Walls and Seals, Surfaces Exposed to Exhaust Gases, High-Pressure Lines, Lavatory Equipment and Miscellaneous Furniture

Description	Strength[b] Hard Ult.	Hard Yield	Soft Ult.	Soft Yield	Specification	Projection, Spot & Seam Welding	Flash Welding	Arc Welding: Inert Gas	Arc Welding: Shielded Metal	Gas Welding	Silver Brazing Alloy
18% Chromium–8% Nickel Steel[a]											
Sheet											
AISI 301	185	140	75	30	AN-QQ-S-772	Good	Fair[c,d]	Good[c]	Good[c]	Good[c]	Fair[c]
AISI 302	185	140	75	30	AN-QQ-S-772	Good	Fair[c,d]	Good[c]	Good[c]	Good[c]	Fair[c]
AISI 321	100	..	75	..	AN-QQ-S-757	Good	Fair[d]	Good	Good	Good	Fair
AISI 347	100	..	75	..	AN-QQ-S-757	Good	Fair[d]	Good	Good	Good	Fair
Bar											
AISI 302[e]	115	85	75	..	AN-QQ-S-771	Good[f]	Fair[c,d]	Good[c]	Good[c]	Good[c]	Fair[c]
AISI 304 Grade 1A	..	..	75	..	FED. QQ-S-763	Good[f]	Fair[c,d]	Good[c]	Good[c]	Good[c]	Fair[c]
AISI 321 Class 8	..	..	75	..	FED. QQ-S-763	Good[f]	Good[d]	Good	Good	Good	Fair
AISI 347 Class 8	..	..	75	..	FED. QQ-S-763	Good[f]	Good[d]	Good	Good	Good	Fair
Tubing											
AISI 302	120	75	75	30	AN-WW-T-855	Good[g]	Fair[c,d]	Good[c]	Good[c]	Good[c]	Fair[c]
AISI 321	..	..	75	..	AN-T-82	Good[g]	Fair[d]	Good	Good	Good	Fair
AISI 321	100	..	75	..	AN-WW-T-858	Good[g]	Fair[d]	Good	Good	Good	Fair
AISI 347	..	..	75	..	AN-T-82	Good[g]	Fair[d]	Good	Good	Good	Fair
AISI 347	100	..	75	..	AN-WW-T-858	Good[g]	Fair[d]	Good	Good	Good	Fair
Inconel[h]											
Sheet, strip	125	90	90	40	AN-QQ-N-271	Good	Fair[d]	Good	Good	Good	Good
Bar, rod, forgings	110	85	100	..	AN-QQ-N-268	Good[f]	Fair[d]	Good	Good	Good	Good
Tubing	120	85	80	30	AN-WW-T-831	Good[g]	Fair[d]	Good	Good	Good	Good
Monel[h]											
Sheet, bar, rod, forgings	100	90	80	40	FED. QQ-N-281	Good	Fair[d]	Good	Good	Good	Good
Tubing	100	90	80	40	.....	Fair[g]	Fair[d]	Good	Good	Good	Good
HANDBOOK Reference Chapters for Processes	..	..	..	..	.	16	17	12	10	5	22

[a] Refer to Chapter 31 for detailed discussion on welding of chromium nickel alloys.
[b] Typical values, given in 1000 psi.
[c] Solution anneal postheat treatment required to dissolve precipitated carbides unless reduced corrosion resistance is acceptable.
[d] Requires specialized technique.
[e] Except free machining bar.
[f] Limited use—welds satisfactorily in thin, smooth sections.
[g] Poor accessibility and fit-up restrict the use of tubular forms. (See Section on Design.)
[h] Refer to Chapter 35 for detailed discussion on welding of nickel and nickel alloys.

Table 4—Superalloys[a]

Applications: Gas Turbine Parts, Heater Combustion Chambers and Other Parts Requiring Good Strength at High Temperatures

Description	AMS No.	Chemical Analysis, % (Nominal)									Typical Tensile Strength[b]						Spot- and Seam Welding	Flash Welding	Arc Welding		Gas Welding	Brazing	
											Room Temperature				1500°F.							Furnace (Copper Alloy)	Silver Alloy
											Cast		Rolled						Inert Gas	Shielded Metal			
		Cr	Co	Ni	Mo	W	Cb	N	Fe	C	Ult.	Yield	Ult.	Yield	Cast, Ult.	Rolled, Ult.							
Bar, rod, sheet, castings forgings																							
N-155 Alloy (Multimet)	5532	20	20	20	3	2	1	0.14	33.5	0.1–0.35	85	55	110	82	47	50	Good[c]	Fair[d]	Good	Good	Fair		Fair
Hastelloy B	..	..	..	..	65	30	..	..	..	5	..	75	55	130	60	60	65	Good[c]	Fair[d]	Good	Good	Fair[e]		Not used
Hastelloy C	5530	15	..	60	17	..	..	..	..	8	..	72	45	130	60	55	65	Good[c]	Fair[d]	Good	Good	Fair[e]		Not used
Haynes Stellite Alloy																							
21	5385	28	65	..	6	..	..	..	..	..	0.2–0.3	101	82	150	105	63	74	Good[c]	Fair[d]	Good	Good	Fair	Limited use	Fair
23	5375	28	65	..	..	6	..	..	..	..	0.4–0.5	105	58	..	..	60	..	Good[c]	Fair[d]	Good	Good	Fair		Fair
27	5378	28	33	32	6	..	..	..	..	..	0.4–0.5	82	46	..	..	..	..	Good[c]	Fair[d]	Good	Good	Fair		Fair
30	5380	28	49	16	6	..	..	..	..	..	0.4–0.5	98	55	..	..	60	..	Good[c]	Fair[d]	Good	Good	Fair		Fair
31	5382	28	56	8	..	7.5	..	..	..	..	0.4–0.5	101	74	150	110	60	78	Good[c]	Fair[d]	Good	Good	Fair		Fair
HANDBOOK Reference Chapters for Processes		..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	16	17	12	10	5	22	22

[a] This term has come into usage to designate a group of alloys which were especially developed for the applications stated. The alloys shown are for the most part proprietary.

[b] Values in 1000 psi.

[c] Welds satisfactorily in thin, smooth sections with good accessibility for welding electrodes.

[d] Requires specialized technique.

[e] Must use a neutral flame to avoid carbon pick-up.

Table 5—Low-Alloy Steels[a]

Applications: Structures, Landing Gear, Engine Mounts, High-Pressure Hydraulic Components, Brackets, Control Rods, Etc.

Description	Specification	Projection, Spot and Seam Welding	Pressure Gas and Flash Welding	Arc Welding		Gas Welding	Brazing	
				Inert Gas	Shielded Metal		Copper	Silver
SAE 4130 Chrome-moly sheet 8630	AN-QQ-S-685 AN-S-12	Good[b]	Good	Not generally used	Good	Good	Good[e]	Good
SAE 4130 Chrome-moly bar 8630	AN-QQ-S-684 AN-S-14	Good[b, d]	Good		Good	Good	Good[e]	Good
SAE 4130 Chrome-moly tube 8630	AN-WW-T-850 AN-T-33	Limited use[b, e]	Good		Good	Good	Good[e]	Good
SAE 4140 Chrome-moly bar	AN-QQ-S-752	Not used	Good[f]		Fair[g]	Fair[g]	Good[e]	Good
SAE 4340 Chrome-nickel-moly bar 8740	AN-QQ-S-756 AN-S-16	Not used	Good[f]		Fair[g]	Fair[g]	Good[e]	Good
HANDBOOK Reference Chapters for Processes	..	16	7, 17	12	10	5	22	22

[a] See Chapter 29 for detailed discussion on welding of low-alloy steels.
[b] Special procedure and equipment required.
[c] Post heat treatment required if grain size control is needed.
[d] Applicable to relatively thin sections with parallel surfaces.
[e] Poor accessibility and fit-up restrict the use of tubular forms. (See Section on Design.)
[f] Post heat treatment for stress relief recommended.
[g] Preheat treatment and postheat treatment recommended.

Table 6—Low-Carbon Steels[a]

Applications: Non-structural Brackets, Control Rods, Spacers

Description	Specification	Projection Spot and Seam Welding	Flash Welding	Arc Welding		Gas Welding	Brazing	
				Inert Gas	Shielded Metal		Copper[b]	Silver
SAE 1020 Low-carbon sheet	AN-S-11	Good	Good	Not generally used	Good	Good	Good	Good
SAE 1025 Low-carbon sheet	AN-S-11	Good	Good		Good	Good	Good	Good
SAE 1020 Low-carbon bar	AN-QQ-S-646	Good[c]	Good		Good	Good	Good	Good
SAE 1025 Low-carbon bar	AN-QQ-S-646	Good[c]	Good		Good	Good	Good	Good
SAE 1025 Low-carbon tube	AN-WW-T-846	Good[d]	Good		Good	Good	Good	Good
HANDBOOK Reference Chapters for Processes	..	16	17	12	10	5	22	22

[a] See Chapter 27 for detailed discussion on welding of low carbon steels.
[b] Post heat treatment required if grain size control is needed.
[c] Applicable to relatively thin sections with parallel surfaces.
[d] See Section on Design.

Accessibility for the welding operation is very important since the probability of making a poor weld increases as the joint to be welded becomes more difficult to reach. Figures 1 and 2 show welded engine mount and landing gear assemblies typical of aircraft structural applications.

Non-Structural Joints—General use is made of arc and gas welding in non-structural assemblies of low-carbon steels, low-alloy steels, 18–8 stainless steels, Inconel, Monel and *Superalloys*.* These assemblies may or may not be subject to loads of a nature requiring stress analysis, but good welding is usually necessary to avoid premature failure of the part. Various joint designs are used. For sheet metal, lap joints are favored because they are easily fabricated and fit-up is not much of a problem. Butt joints are acceptable, but require careful fit-up, and in thicknesses of $^1/_{16}$ in. or more the edges usually are beveled to secure full root penetration. Tubing or bar is frequently welded to sheet material to form an attachment point or boss.

Figures 3 and 4 show applications of the non-structural use made of arc and oxy-acetylene welding.

Oxy-hydrogen Welding of Aluminum.—Although nearly all forms of joint design in aluminum can be welded using an oxy-hydrogen torch, the practice must be confined to a relatively few weldable alloys (see Table 1). After such welding, aluminum must be promptly defluxed to prevent corrosion, consequently joints in which flux may be trapped should be avoided. Butt joints, including those in which the edges are flanged and melted down flush, are most preferred. The strength of such joints is comparable to the annealed value for the base metal. A typical assembly is shown in Fig. 5.

Fig. 1.—Arc- and Gas-Welded Engine Mount

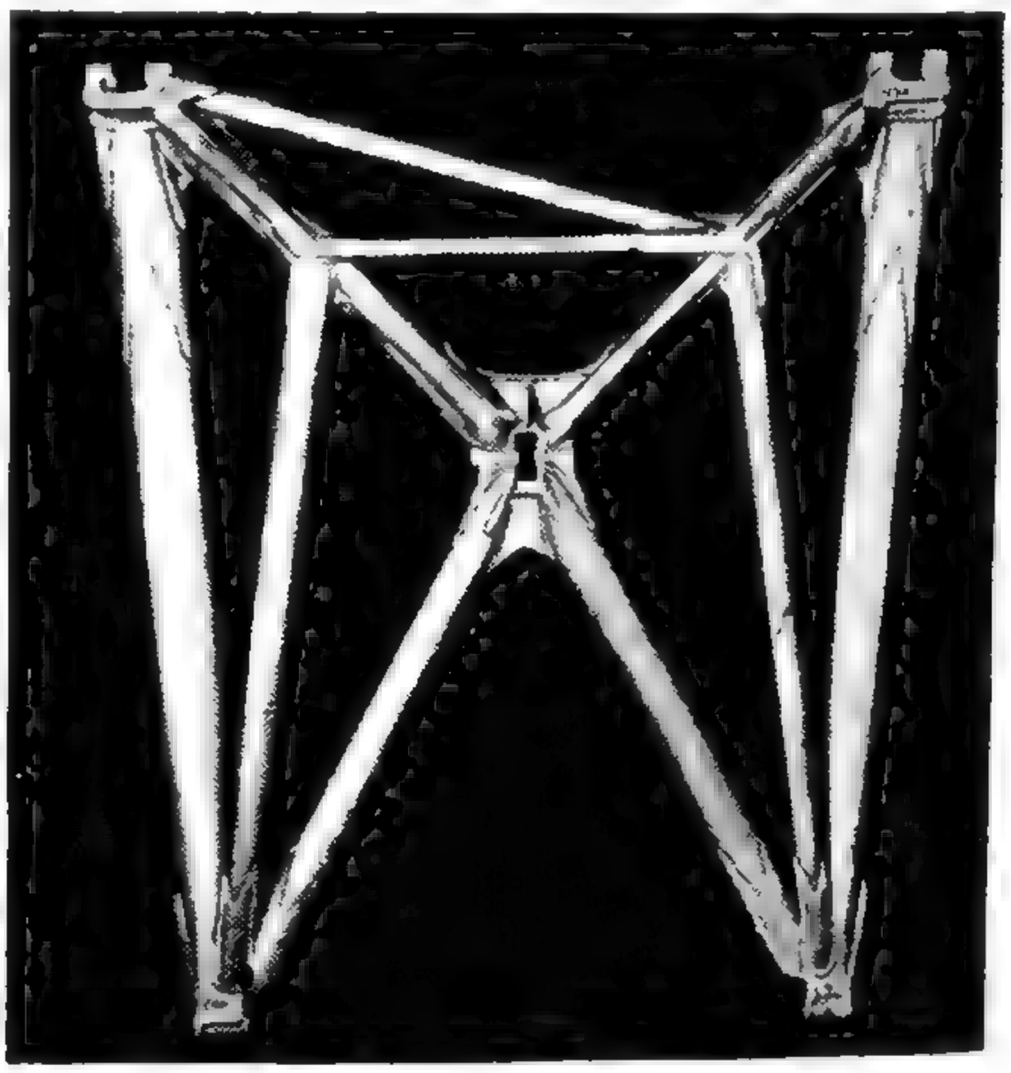


Fig. 2.—Arc-Welded Landing Gear Truss

Flash Welding

Allowable Strengths.—The low-alloy steels are the only materials now regularly fabricated by flash welding for aircraft structural applications. The allowable tensile strengths for welds in such steels are found in Specification ANC-5 and are subject to revision as the procedures or materials are improved. At present, joints in normalized tubing, as-welded, are considered equal to the unwelded tubing. For heat-treated tubing, welded after heat treatment, an efficiency factor of 1.00, based on the ultimate tensile strength of normalized tubing, is allowed. For joints in tubing, heat-treated after welding, the majority of aircraft companies prefer an efficiency factor of 1.00, based on test and close quality control. ANC-5 allowables, however, are restricted to efficiency factors of 0.80 and 0.90, due to the reluctance of the services to accept the higher value in view of adverse service experience and the need for a margin of safety in welds with possible hidden defects.

* Heat-resisting alloys containing molybdenum, nickel, chromium, cobalt or tungsten. (See Table 4.)

Joint Design.—The large majority of flash-welded assemblies used in aircraft consists of end fittings machined from bar stock or forgings, flash welded to each end of tubing of standard diameter and wall thickness. It is desirable to locate the weld as near to each end of the assembly as possible to reduce the total amount of machining on the end fitting. This location is also desirable from a stress standpoint for compression members since it tends to minimize any buckling tendency. On the other hand, a good weld is mandatory and all the necessary clamping and backing provisions to introduce adequate current, hold alignment and prevent slippage of the part during upset must be considered. The design data given for clamping length, material loss, die space, etc., for flash welding in the AWS *Recommended Practices for Resistance Welding* (see Chapter 17) are amply conservative to ensure production of good welds. Although it is likely that some departure from these values can be made in the interest of reduced machining cost, no significant change should be made without appreciable testing.

Applications.—Assemblies made by this process are landing gear struts and braces, engine mount members and wing spar members. Also included are rod assemblies for engine control, operation of cowl flaps, wing flaps, ailerons, elevators, rudders, trim tabs and doors of all kinds. The heads of some hydraulic cylinder assemblies are flash welded to the barrels and the piston head to the piston rod.

(See Figs 6 and 7.)

Pressure Gas Welding

Allowable Strengths.—The allowable strengths for pressure gas-welded joints are the same as those used for flash welding. Test results on welded low-alloy steel parts heat treated to the range 180,000 to 220,000 psi. consistently show 100% joint efficiency.

Joint Design.—The design of joints is somewhat similar to that for flash welding. Most applications use tubular sections. Pressure gas welding requires properly prepared ends for consistently high joint quality; abutting faces must be smoothly machined precisely at right angles to the axis of the tube. Provision must be made for applying the welding force axially along the work. Other important design considerations are shown in Fig. 8.

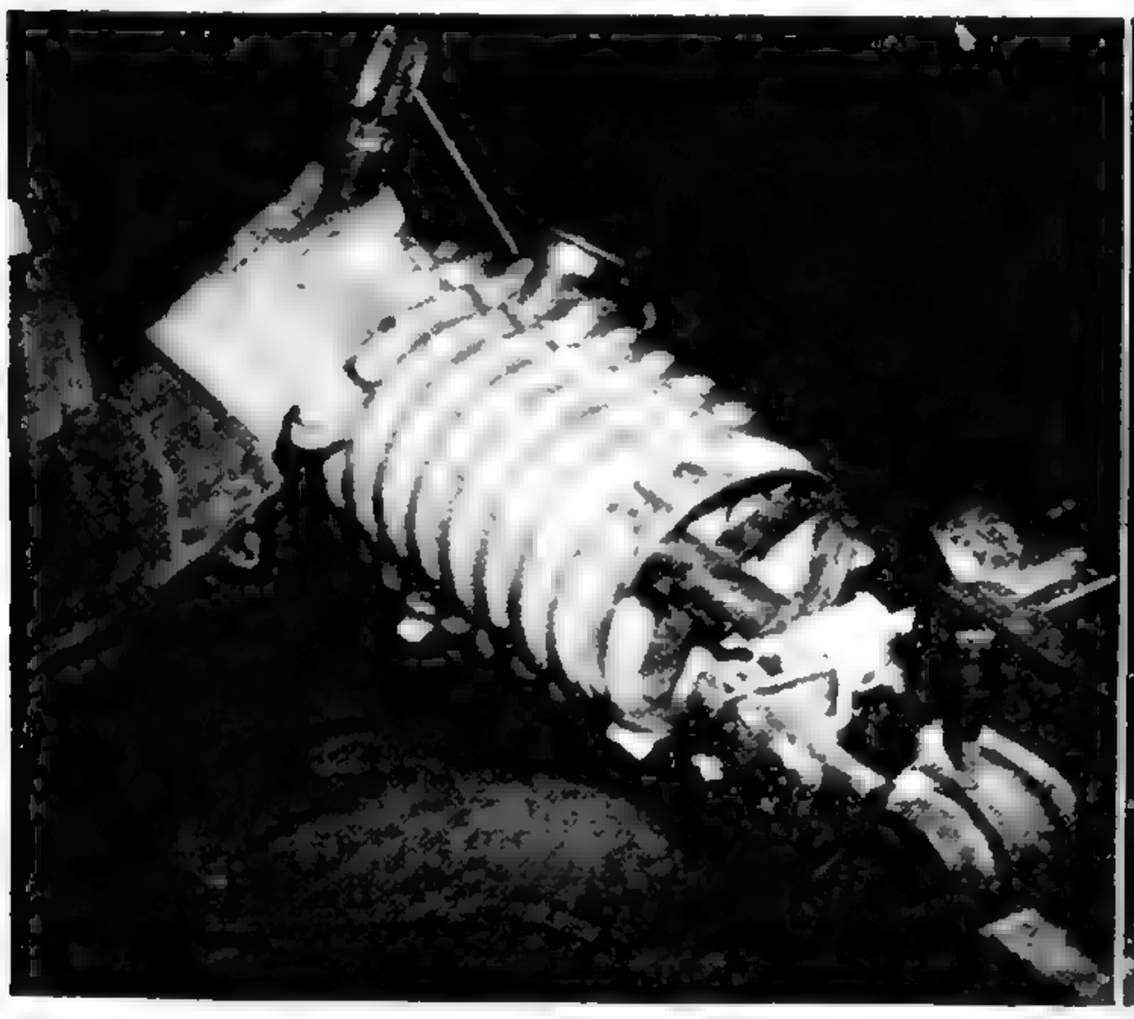


Fig. 3.—Arc-Welded Boiler

Fig. 4.—Oxy-Acetylene Welded Chrome-Moly Steel Brackets

Applications.—Pressure gas welding is used in the fabrication of heavy structural units such as landing gear. Light work for pressure gas welding is considered heavy work for flash welding and there is some overlapping of the processes. Most pressure-gas welded assemblies have a wall heavier than 0.1 inch.

Projection, Spot and Seam Welding

Allowable Strengths and Design Restrictions.—Specifications ANC-5, AN-

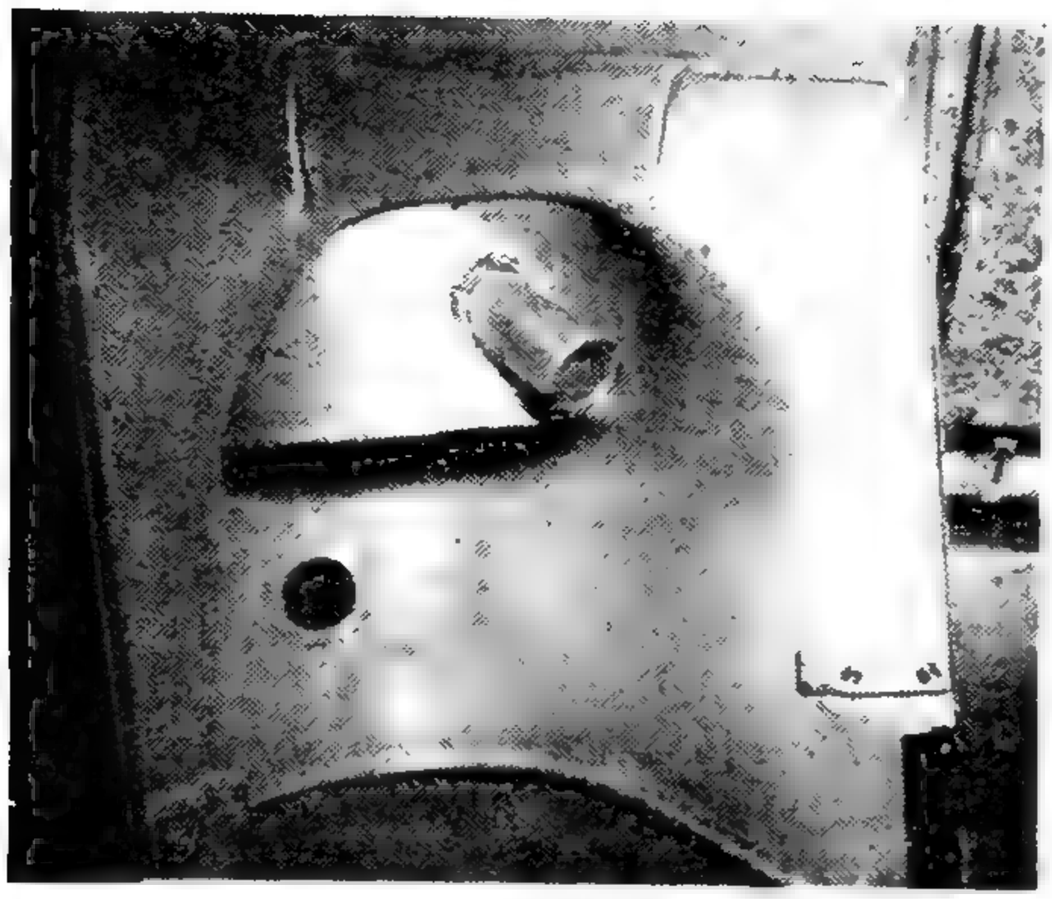


Fig. 5.—Oxy-Hydrogen Welded Aluminum Alloy Cowling Assembly

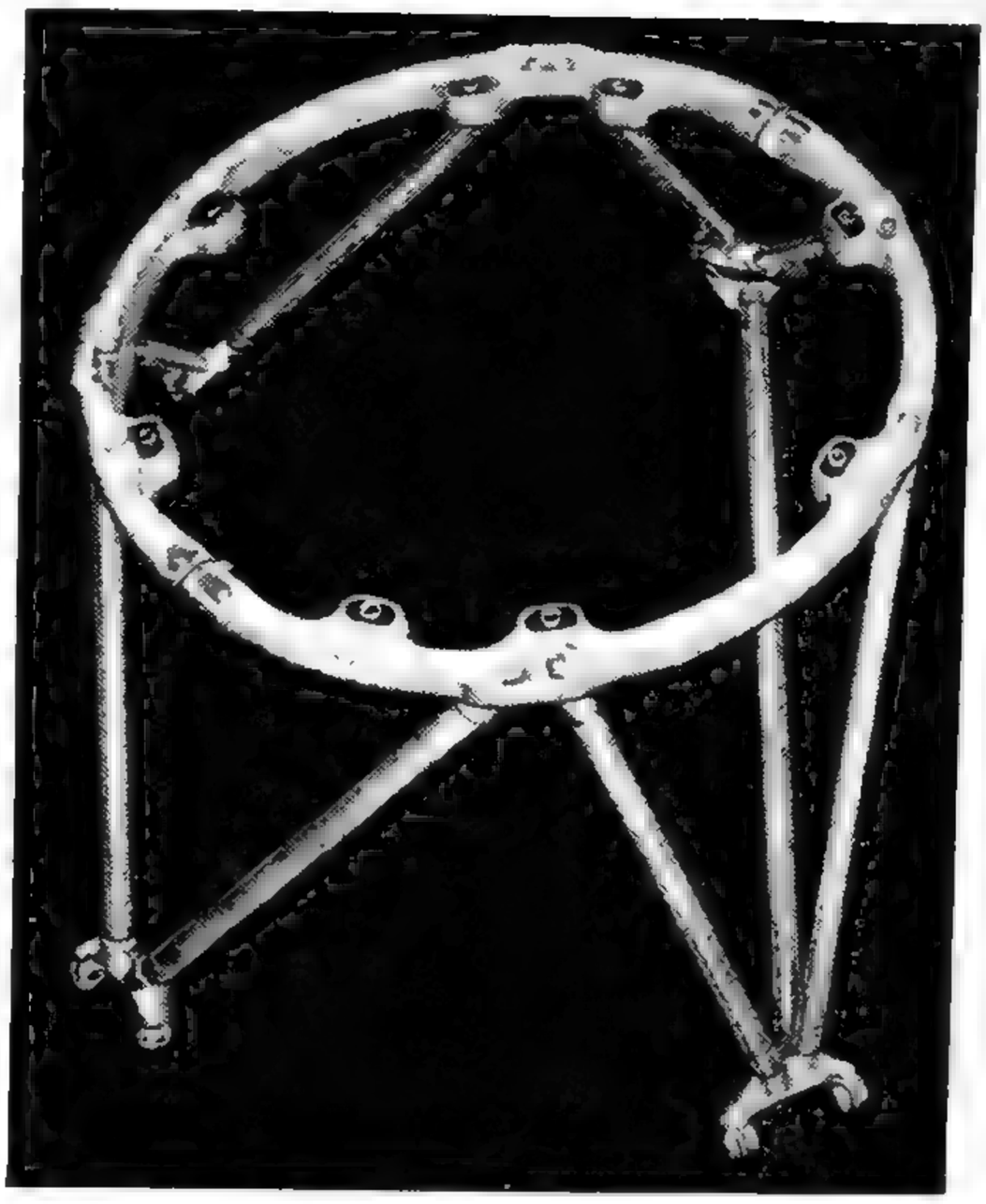


Fig. 7.—Flash-Welded Engine Mount

Fig. 6.—Flash-Welded Crew Nacelle Spar Assembly

Diagonal braces also flash welded.

W-30, AN-W-32, AAF 20011 and the Army and Navy Design Handbooks all impose restrictions on the application of spot welding. Aluminum joints must be of three thicknesses or less, and the maximum thickness difference must not be more than 4× the thickness of the thinner outer sheet. Bare structural alloys must be welded to each other only with special permission contingent upon adequate corrosion protection. Structural fittings are not permitted to be fabricated by piling up several thicknesses and spot welding. The welding of low-alloy (heat-treatable) steels and the design of structural assemblies must be approved by the procuring agency. No strengths have been established by specification for projection welds or for seam welds (other specification requirements on these processes appear in the Quality Control Section). The maximum design load per spot is specified not to exceed the values given in Table 7.

Joint Design.—In designing a spot-welded joint the first consideration (after strength) is the amount of material overlapped and the spacing between successive welds in a row. Table 8 gives some typical values of overlap and weld spacing used in aircraft.

Certain general practices in the design of spot-welded parts bear observation and comment. Weldments involving severely curved or tubular sections are

Table 7[a]—Maximum Design Shear Strength Per Spot Weld, Lb.

Nominal Thickness of Thinner Sheet, In.	Uncoated Steels and Nickel Alloys[b]			Clad and Bare Aluminum Alloys[b]				Magnesium Alloys	
	(1) Ult. 150 and Over	(2) Ult. 70 to 150	(3) Ult. 70 and Below	(4) Ult. 56 and Over	(5) Ult. 28 to 56	(6) Ult. 19.5 to 28	(7) Ult. 19.5 and Below	(8)	(9)
0.008	120	85	70	..	..	..	..	..	..
0.012	220	155	120	60	52	24	16	..	..
0.016	320	235	170	86	78	56	40	..	..
0.020	425	310	225	112	106	80	62	51	69
0.025	580	425	320	148	140	116	88	71	97
0.030	750	565	403	..	..	..	..	..	..
0.032	..	..	..	208	188	168	132	103	139
0.040	..	..	..	276	248	240	180	138	186
0.042	1275	920	712	..	..	..	..	..	..
0.050	1700	1205	955	..	..	..	..	..	..
0.051	..	..	..	384	354	329	240	186	251
0.062	2307	1642	1374	..	..	..	..	..	..
0.064	..	..	..	552	500	451	320	243	328
0.070	2975	1982	1628	..	..	..	..	..	..
0.072	..	..	..	678	589	524	364	279	379
0.080	3540	2405	1960	..	..	..	..	..	..
0.081	..	..	..	842	691	620	424	320	435
0.091	..	..	..	1020	810	703	484	368	500
0.094	4288	2975	2443	..	..	..	..	..	..
0.102	..	..	..	1230	960	760	548	433	586
0.109	4955	3540	2938	..	..	..	..	..	..
0.114	..	..	..	1465	1085	803	591	488	658
0.125	5665	4052	3440	1698	1300	840	629	545	735

[a] From ANC-5.

[b] Ultimate strength of the applicable alloy in 1000 psi. determines the column to be selected.

NOTE: (1) Steel, 18-8, 1/2 hard to full hard. (2) Steel, 18 8 annealed and 1/4 hard, also low alloy. (3) Steel, plain-low carbon, 1010, 1020, etc. (4) 14S-T6, 17S-T4, 24S-T3, 75S-T6, R-301, R-303. (5) 52S-H34, 52S-H38, 53S-T6, 61S-T6. (6) 2S-H18, 3S-H14, 61S-0, 61S-T4, 52S-0. (7) 2S-0, 2S-H14, 3S-0. (8) AN-M-30. (9) AN-M-28, AN-M-29.

Table 8—Spot-Weld Joint Design Data[a]

Thickness of Thinner Sheet, In.	Aluminum and Magnesium		Steel[c] and Nickel Alloys	
	Overlap, In.	Weld Spacing,[b] In.	Overlap, In.	Weld Spacing,[b] In.
0.008	...	..	5/16	3/16
0.012	...	..	5/16	1/4
0.016	3/8	3/8	3/8	5/16
0.020	3/8	3/8	3/8	5/16
0.025	7/16	1/2	7/16	7/16
0.030	...	..	7/16	1/2
0.032	1/2	1/2	...	...
0.035	...	..	7/16	9/16
0.040	1/2	5/8	...	...
0.042	...	..	1/2	5/8
0.050	...	..	1/2	3/4
0.051	5/8	3/4	...	...
0.062	...	..	9/16	1
0.064	3/4	7/8	...	...
0.072	3/4	7/8	...	...
0.078	..	..	5/8	1 1/4
0.081	3/4	7/8	...	...
0.093	...	..	1 1/16	1 1/2

[a] Values in this table are typical for the aircraft industry.
[b] It is undesirable to space the welds more closely than shown (except for seam welding). Wider spacings should be used wherever possible.
[c] Corrosion-resistant, low-alloy and plain low-carbon steel.

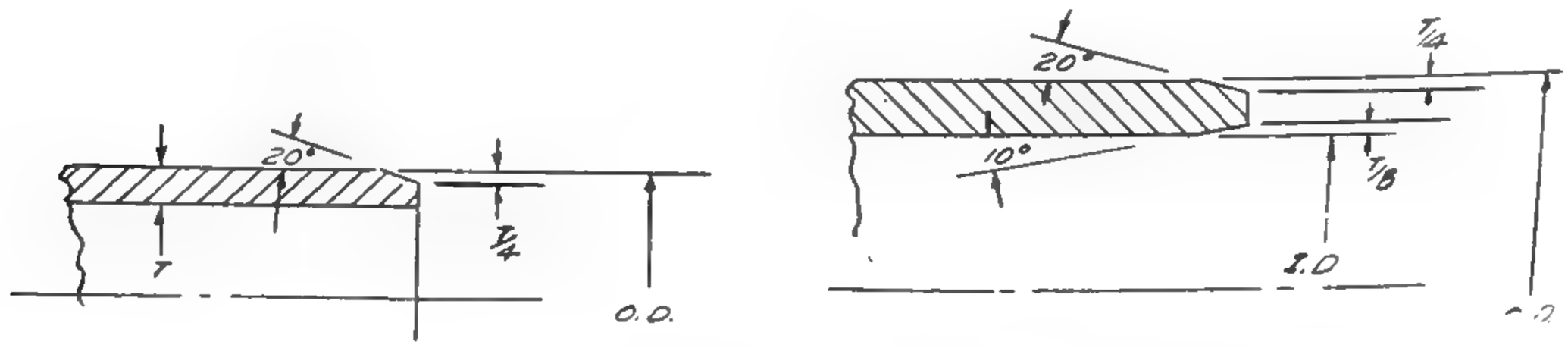
generally difficult to produce with top quality. There is frequently difficulty in making the details fit together. With electrode faces too flat to fit the curved part, distortion results; with electrodes severely contoured, poor welds may result. If the tubes are small in diameter and the distance from the end to the point of welding is appreciable, the arm inserted into the tube will bend, also contributing to poor welding. Soft aluminum alloys are not entirely satisfactory for aircraft spot welding since they require higher currents, producing overheating of the electrodes, poor external weld appearance and severe indentation.

Figure 9 shows a number of different spot-weld joint designs and Fig. 10 a number of seam weld joint designs with comments on the desirability of each.

Complicated assemblies of aluminum or magnesium alloys which require appreciable benchwork between successive welding operations may become contaminated by handling or by oxidation of the weld areas due to elapsed time after deoxidation treatments and this may result in lowered weld quality. Careful design can minimize this difficulty.

Design for projection welding in aircraft has not been appreciably developed and has been used only for steels and nickel alloys. Design for seam welding is essentially the same as for spot welding with regard to overlap. Spot spacing is usually not specified, but rather the degree of pressure tightness in terms of a required pressure test. Chapter 16 contains further information on spot, seam and projection welding.

Applications.—See Figs. 11 to 14 for typical spot, roll spot and seam welding applications.



(*a*) For wall thicknesses up to 0.250 in. (*b*) For wall thicknesses over 0.250 in.

Fig. 8.—Joint Preparation for Pressure Gas Welding

NOTE: Welds should not be located closer to a change in section than 4 times wall thickness. Amount of metal lost during welding approximately equal to wall thickness.

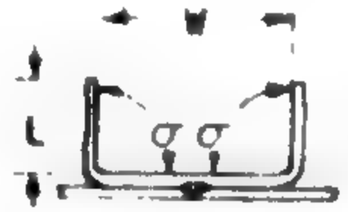
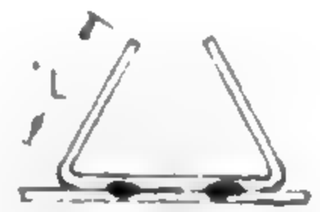
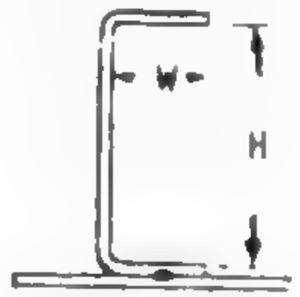
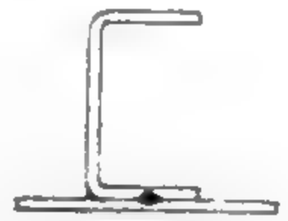
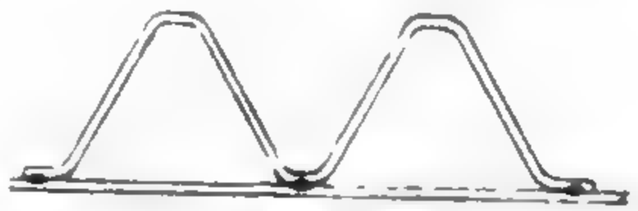
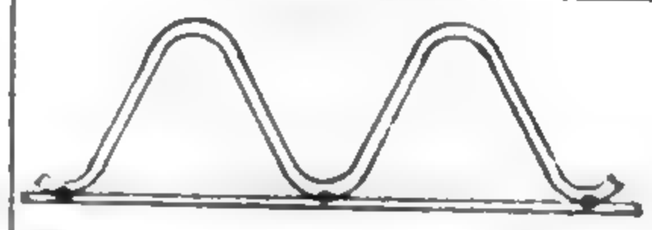
GOOD	FAIR	POOR	BAD	BAD
σ = 90° OR MORE L = 2 IN.OR LESS	σ = 90° OR MORE L = OVER 2 IN.	σ = 60° TO 90° L = OVER 2 IN.	σ = UNDER 60°	σ = OVER 3°
 σ = 90° OR MORE L = 2 IN.OR LESS W = OVER 3/4 IN.	σ = 90° OR MORE L = 4 IN.TO 12 IN. W = OVER 1 1/2 IN.	 L = OVER 2 IN. W = 7/16 IN.THRU 5/8 IN.	W = UNDER 7/16 IN.	ALUMINUM & MAGNESIUM ALLOYS
	 H = 2.5W OR MORE	 H = 1.75W TO 2.5W	H = UNDER 1.75W	
H = 2 IN.OR LESS W = OVER 3/4 IN.	H = 2 IN. OR LESS W = 5/8 IN.TO 3/4 IN.	 H = 2 IN.TO 4 IN. W = 7/16 IN.TO 5/8 IN.	 ROUND CONTACT AS SHOWN	
R = 10 IN. OR MORE D = 20 IN. OR MORE	R = 4 IN.TO 10 IN. D = 8 IN.TO 20 IN.	R = 4 IN.OR MORE D = 8 IN.OR MORE	R = UNDER 4 IN. D = UNDER 8 IN.	

Fig. 9.—Aircraft Spot-Welding Design

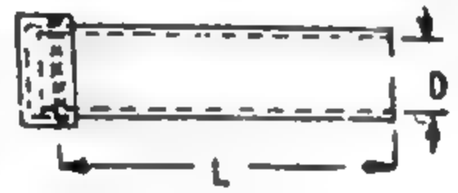
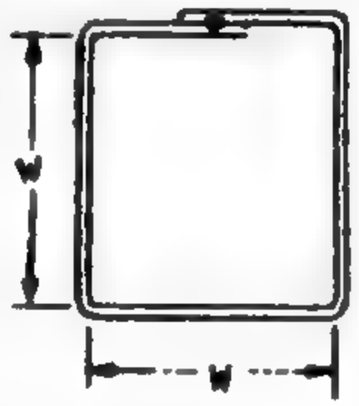
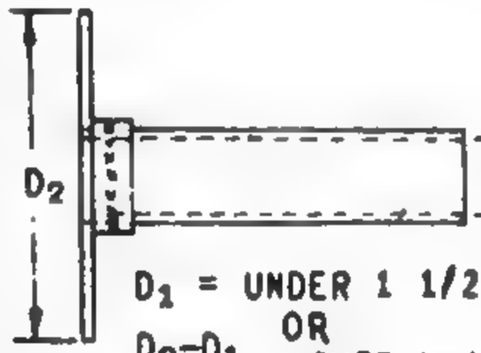
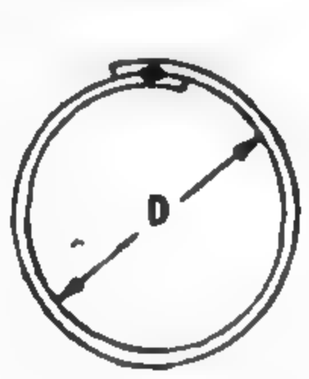
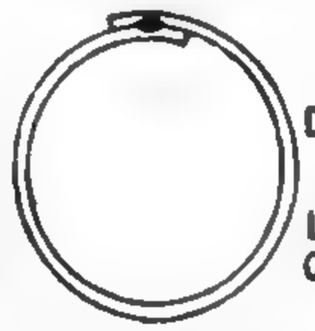
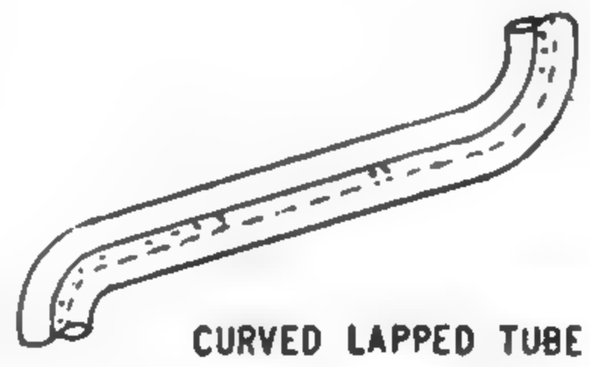
GOOD	FAIR	POOR	BAD	LIMITED
σ = 90° OR MORE	σ = 90° OR MORE H = 6 IN. TO 3 FT	σ = 85° TO 90° H = 4 IN. TO 6 IN.	σ = UNDER 85° H = UNDER 4 IN.	 L = OVER 24 IN. D = UNDER 1 1/2 IN. OR L/D = OVER 3/1 RATIO
 W = 4 IN. OR MORE LENGTH = THRU 24 IN.	W = 4 IN. OR MORE LENGTH = OVER 24 IN.	"SIDE" LAP OR W = 2 IN. TO 4 IN. LENGTH = OVER 24 IN.	"SIDE" LAP OR W = UNDER 2 IN. LENGTH = OVER 24 IN.	 D_1 = UNDER 1 1/2 IN. OR $\frac{D_2-D_1}{2}$ = OVER 4 IN.
 D = 4 IN. OR MORE LENGTH = UNDER 24 IN.	 D = 4 IN. OR MORE LENGTH = OVER 24 IN.	D = 1 1/2 IN. TO 4 IN. LENGTH = OVER 24 IN.	D = UNDER 1 1/2 IN. OR LENGTH= OVER 6 FT.	BAD DO NOT ROLL SPOT OR SEAM WELD SCARFS ON TUBES.
FLANGED TUBE: INSIDE FLANGE CURVE = 3 FT RADIUS OR MORE	FLANGED TUBE: INSIDE FLANGE CURVE = 2 FT TO 3 FT RADIUS	CURVED LAPPED TUBE: DIAMETER = UNDER 8 IN. LENGTH = OVER 16 IN. CURVE = UNDER 3 FT RADIUS	 CURVED LAPPED TUBE	

Fig. 10.—Aircraft Seam-Welding Design

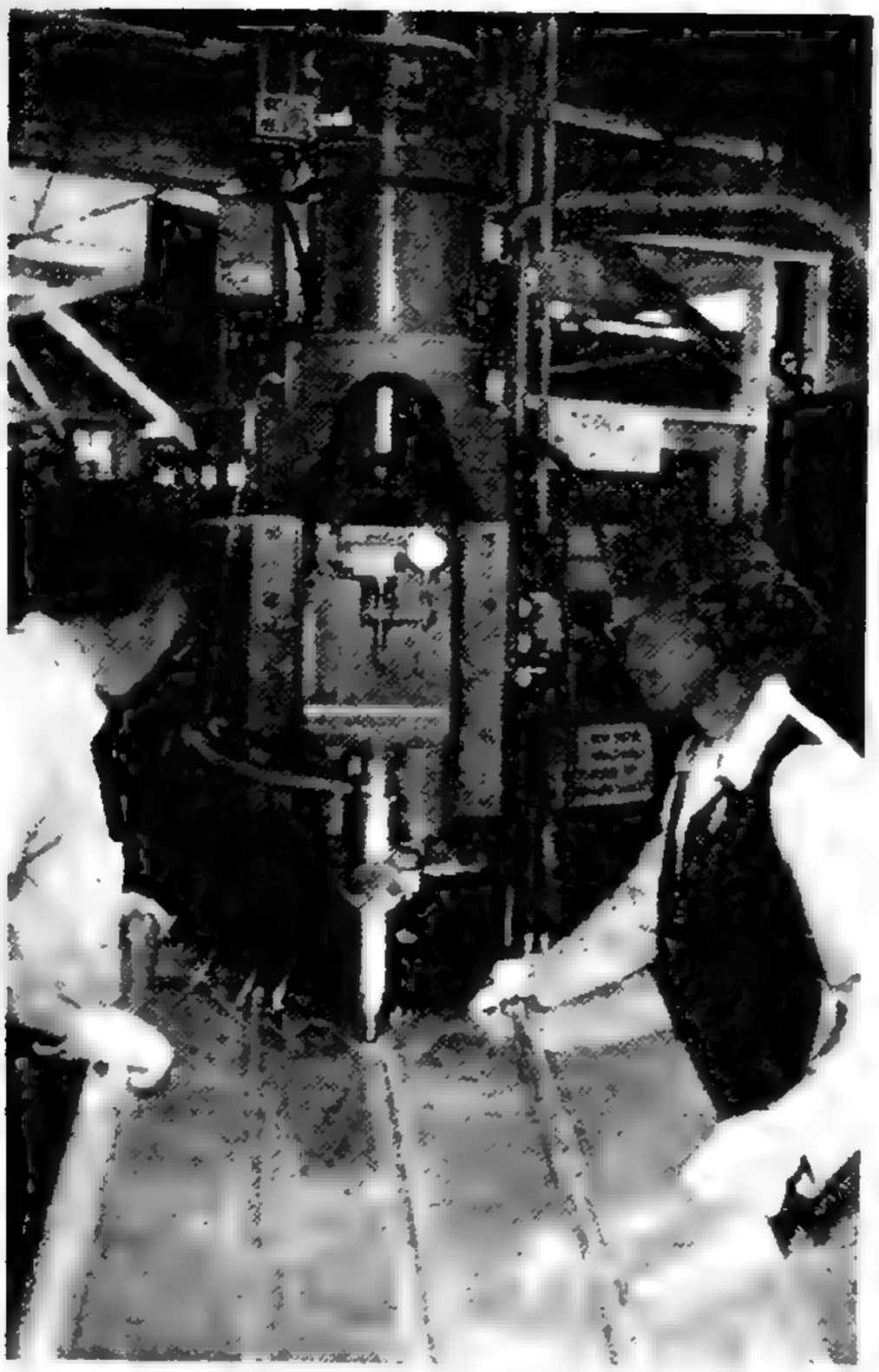


Fig. 11.—Spot Welding Aluminum Alloy Tail Boom Segment

Fig. 12.—Spot-Welded Aluminum Alloy Engine Cowl

the computation of the strength of the joint have been established for it.

Results from a number of tests on aluminum alloys are given in Table 9.

Typical Applications.—Nearly any type of joint can be welded using this process, but a very low upstanding flange is probably the ideal since it can be welded with no (or very little) added filler metal, and at very high speeds.

Figures 15 to 18 show typical assemblies fabricated using this process. (See also Chapter 12 for further information on inert-gas metal-arc welding.)

Inert-Gas Metal-Arc Welding

Strength Considerations.—Since this process is not generally applicable to structure alloys for aircraft, no rules for

Brazing

Strength of Joints.—In aircraft design brazed joints must be stressed entirely in shear, since tension loads may cause failure

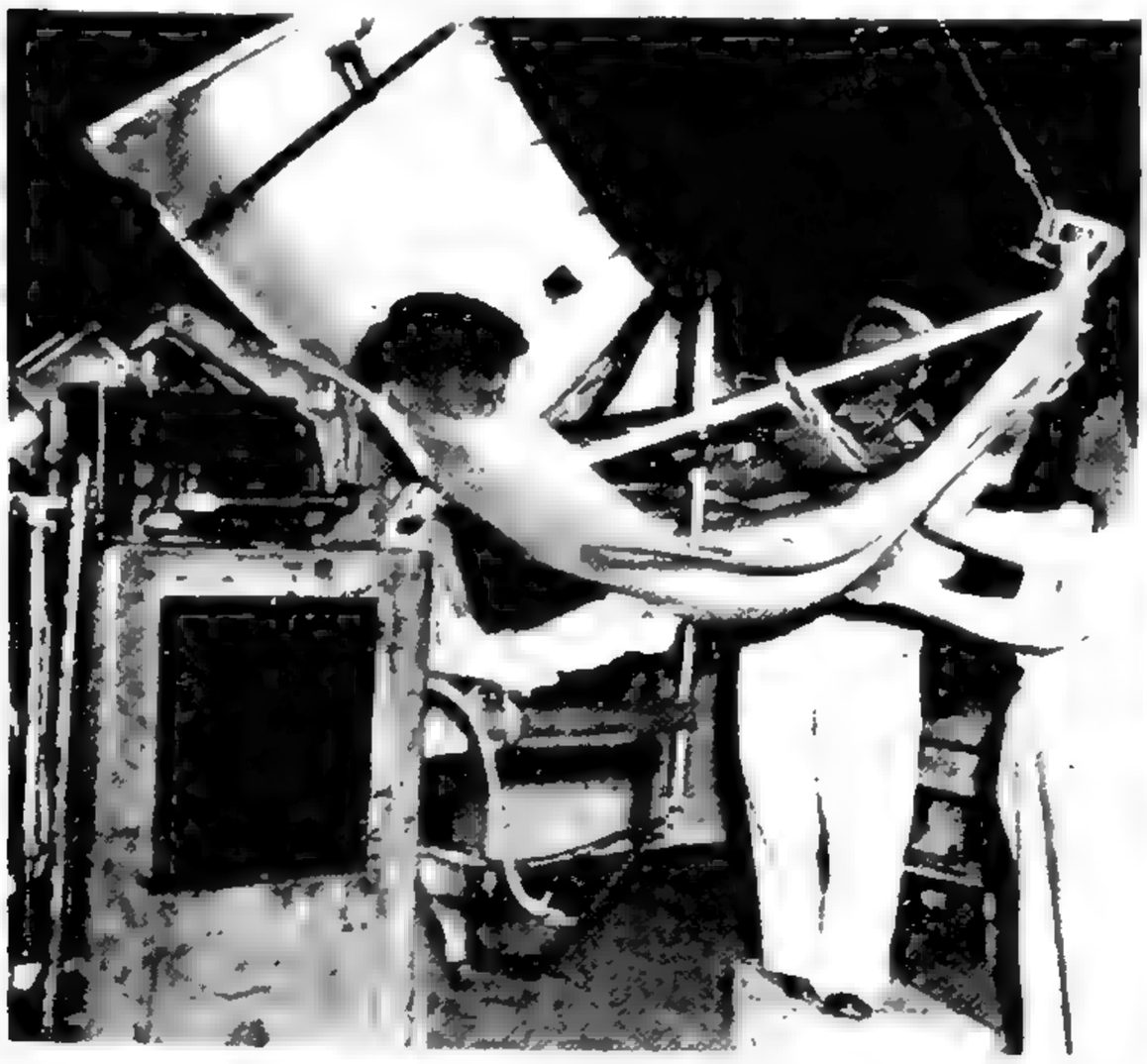


Fig. 13.—Spot Welding Inner Ring

Fig. 14.—Spot Welding Body Skin Panels

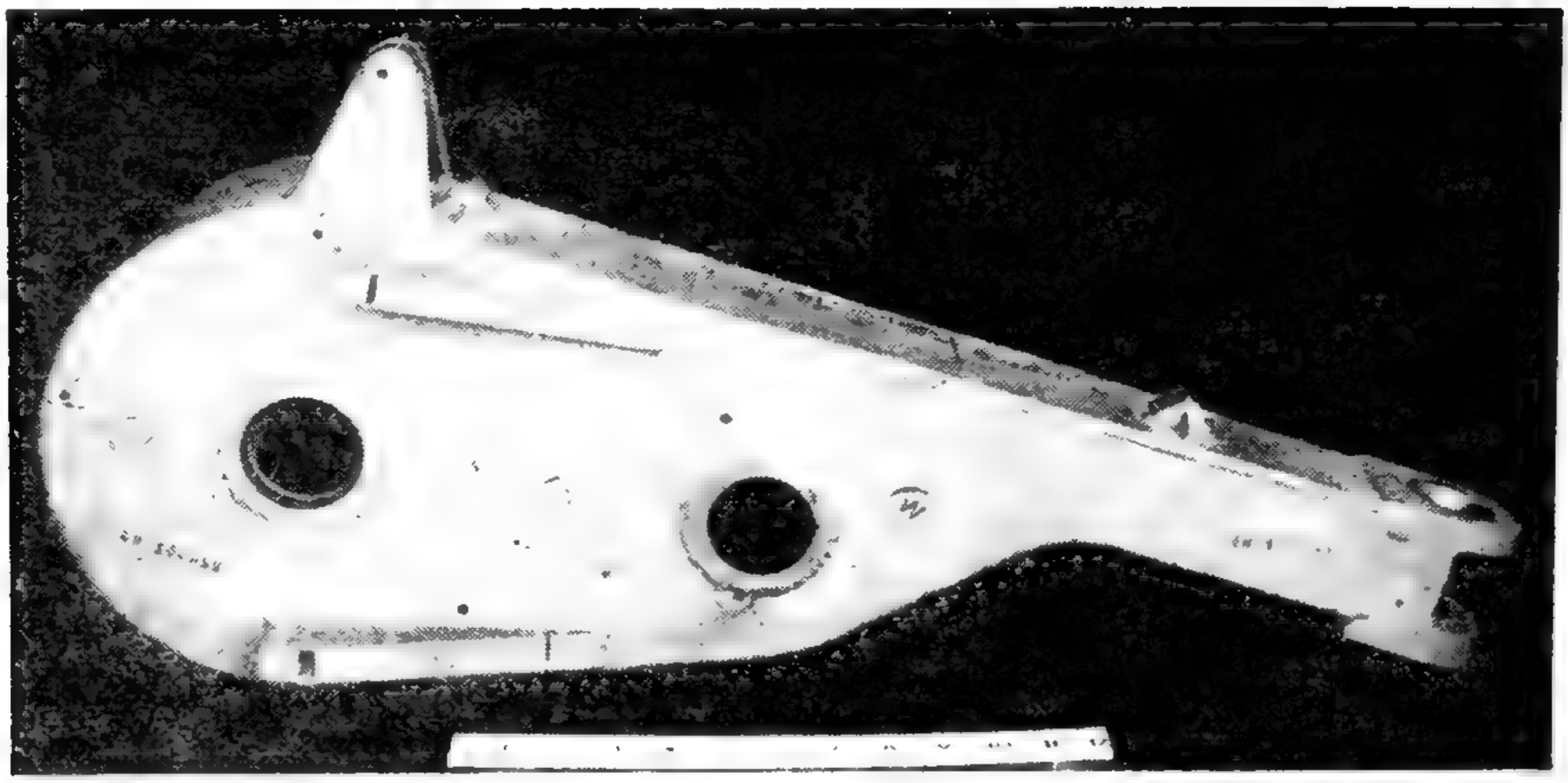


Fig. 15.—Inert-Gas Metal-Arc Welded Magnesium Pilot Control Column

Table 9—Strengths of Welds in Aluminum Alloys

Argon Shielded Arc, A.C. Machine

Alloy	Thickness, In.	Number of Specimens	Ultimate Tensile Strength Average, Psi.	Ultimate Tensile Strength Minimum, Psi.
		Butt Weld in Sheet		
52S-O	0.102	59	27,500	21,130
52S-O	0.040	6	24,600	23,700
3S-O	0.064	2	16,400	16,000
61S-O	0.040	2	17,000	17,000
61S-T4	0.040	1	25,600	25,600
61S-T4	0.064	3	22,500	21,800
61S-T4	0.072	3	27,900	24,600
		Butt Weld and Reinforcing Strap		
61S-T4	0.072	3	28,300	26,000
		1-In. Lap and Double Fillet Weld		
61S-T4	0.040	2	23,900	22,500
61S-T4	0.064	8	25,600	24,300

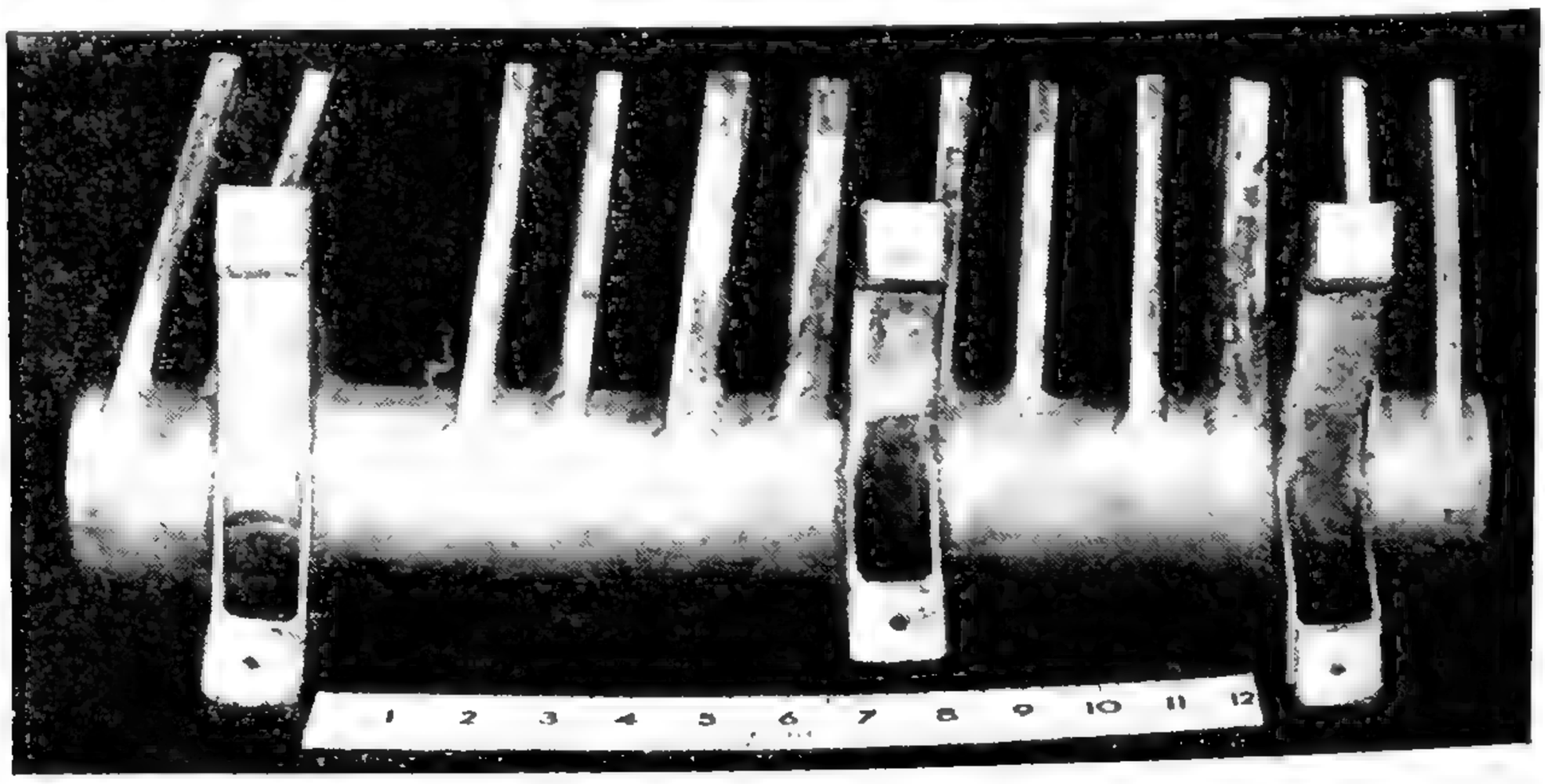


Fig. 16.—Inert-Gas Metal-Arc Welded Magnesium Pulley Bracket

Alignment of supports is very important for machining and installation.

at low values by *peeling*. While brazing is frequently used where low or no-load conditions are encountered, it may be used in structural applications, and parts furnace-brazed with copper may be heat-treated without destroying the bond. Many factors other than design, such as surface roughness, cleanliness, filler metal, base metal, heating process, etc., affect the strength of a brazed joint. Consequently, the maximum design strength specified (ANC-5) for steels and nickel alloys is 15,000 psi.

Brazing is usually not used where elevated temperatures are to be expected. Table 10 shows the results of some tests on low-alloy steels at various temperatures. (See Chapter 22 for further information on brazing.)

Joint Types.—The requirements for

Table 10—Test Results on Brazed Joints in Low-Alloy Steel at Elevated Temperatures

Temperature, °F.	Shear Strength, Psi — Furnace Brazing (Copper alloy) (Lap Joint in Plate)[a]	Torch Brazing (85% Silver, 15% Manganese) (Plug and Ring)[a]
Room	17,525	24,900
400	15,580	20,800
800	14,060	20,100
1000	9,700	12,800
1200		7,810

[a] Results from lap joints in plate are usually lower than plug and ring results.

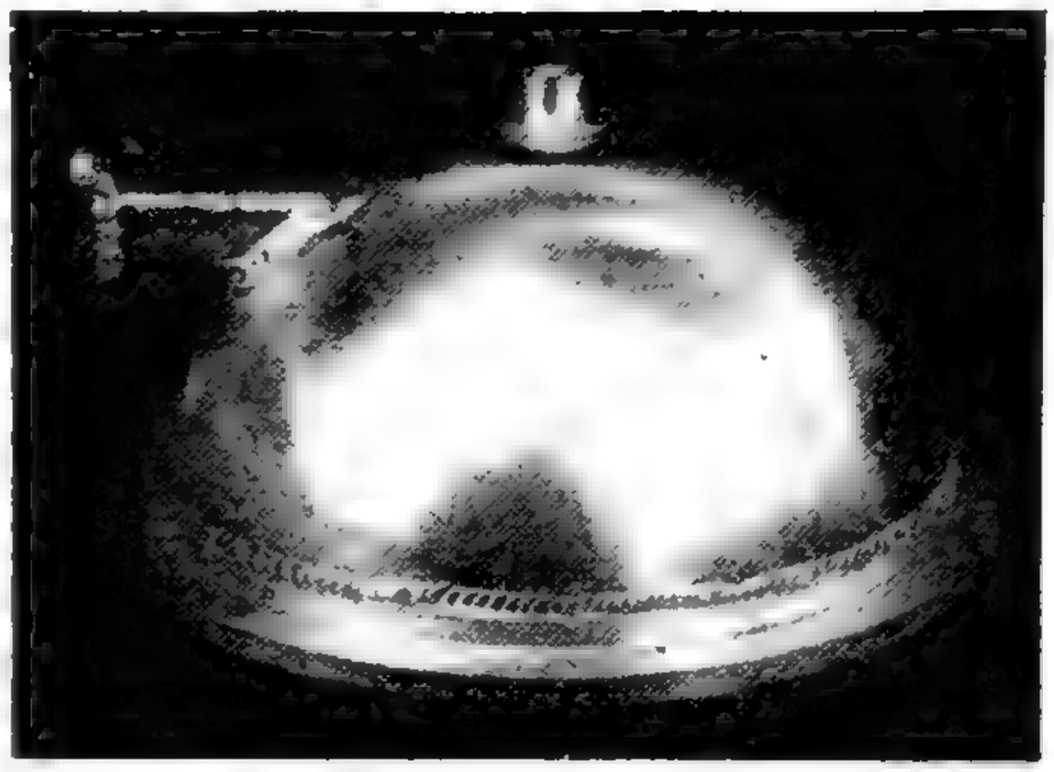


Fig. 17.—Inert-Gas Metal-Arc Welded Hydraulic Pressure Reservoir Fabricated from Drawn Magnesium Dome and Magnesium Plate Base

loading only in shear limits to four the types of joint which can be used.

(*a*) Sleeve type (tube in tube; rod in socket)

(*b*) Collar type (tube or rod through plate)

(*c*) Plate to plate (lap joint)

(*d*) Combinations of the above.

Fit-up Tolerances.—Tests of furnace brazed sleeve or collar type joints using copper brazing alloys have shown some increase in average strength with interference fits, but there is a wider range of joint strength, and a longer soaking time in the furnace is necessary for full joint

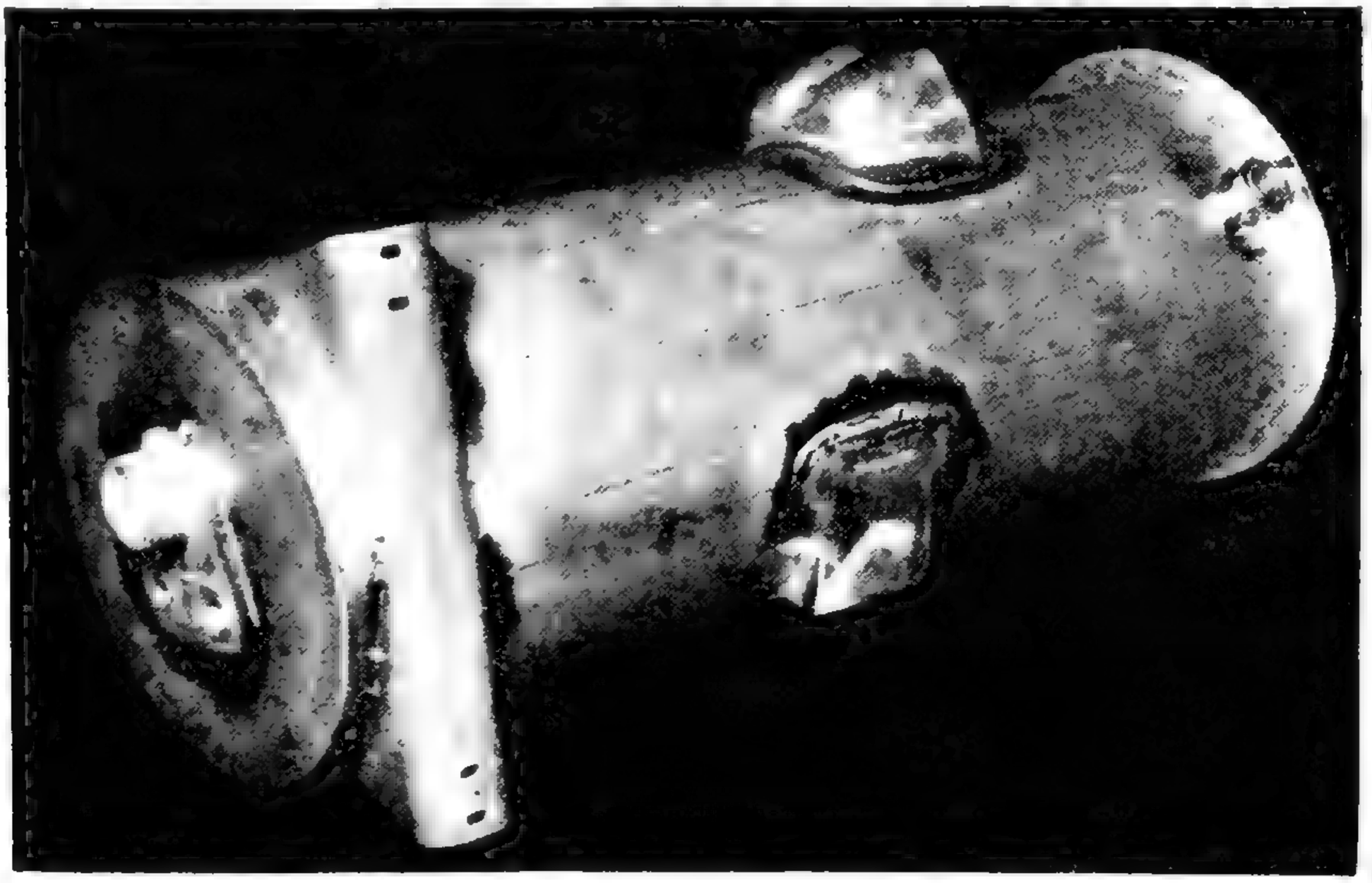


Fig. 18.—Inert-Gas Metal-Arc Welded Hydraulic Reservoir Tank Composed of AZ61 Magnesium Sheet and AZ92 Magnesium Casting

penetration. Aircraft practice now is to provide a fit from 0.002 interference to 0.005 clearance. For silver alloys the fit is in the range from 0.003 to 0.010 clearance.

Suface Roughness.—Surface roughness has been found to be not critical within the limits of 40 to 250 micro-inches RMS (as defined by the National Aircraft Standards Committee).

Applications.—Furnace brazing with copper alloys has been utilized mostly for parts prefabricated from low-alloy and plain-carbon steels. Some structural members have been fabricated by this process and heat treated to relatively high strengths after brazing.

Brazing, using silver alloys, can be applied to most aircraft metals, except aluminum and magnesium. Because of the low melting point of the silver alloys, the assemblies are not generally heat treated after brazing, and since lower temperatures (than for welding) may be used, this process is advantageous in joining thin sheet metal to reduce warpage. Brazing with silver alloys has been used to some extent for structural applications, but receives its broadest use in non-structural design. Torch brazing using aluminum alloys is not practiced extensively, welding being preferred. Furnace and dip brazing have been used in the fabrication of aluminum alloy radiators, tanks, grills, fittings and tubular assemblies.

Soft Soldering

Applications.—The use of lead-tin solder is very restricted in aircraft. It is used for connections in the electrical system where solderless connectors cannot be used; for the attachment of brass instruction plates to landing gear shock struts and similar members; and for the sealing of threaded high pressure hydraulic assemblies (such as piston heads to piston rods). (See Chapter 23 for further information on soft soldering.)

FABRICATING PRACTICES AND PROCEDURES

Arc and Gas Welding

Jigging Methods.—In order to control dimensions and warpage, it is regular practice in aircraft welding to utilize a jig of some sort. The best designed jigs incorporate such features as easy positioning, so that downhand welding can nearly always be used; ample clearance, so that the welder will not be cramped; and sturdy construction to withstand rough handling in the shop or thermal stresses due to preheating, welding and postheating.

Figures 19 and 20 show typical jigs used for gas and arc welding.

Fit-up.—A quality welding job is impossible without good fit-up. In welding butt joints, every effort is made to keep the root opening to less than half the thickness of the material being welded. This is accomplished by careful machining and considerable benchwork of the usual metal fitting variety. If the sheet thickness exceeds $^1/_8$ in., the edges are usually

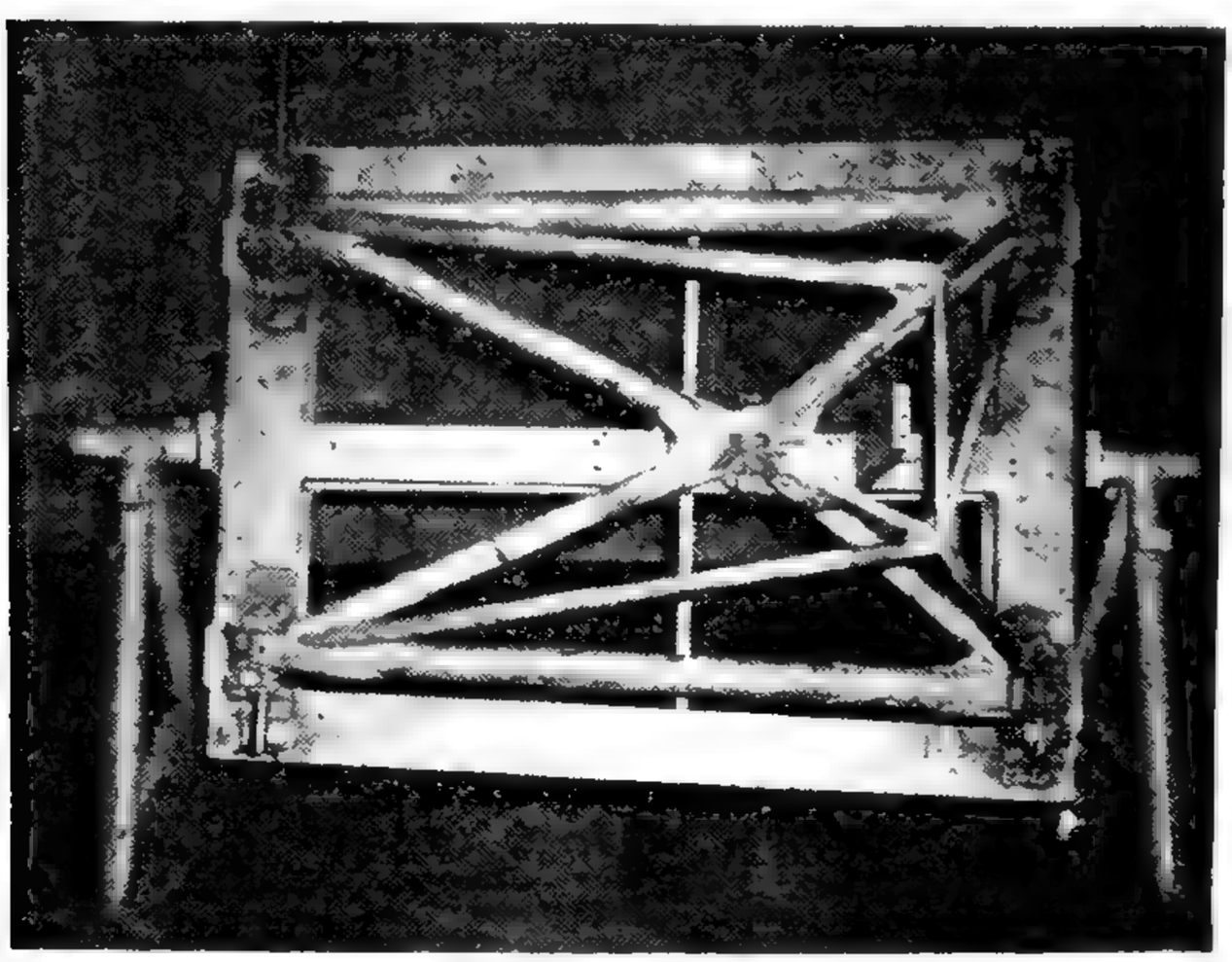


Fig. 19.—Jig for Arc Welding Landing Gear Truss

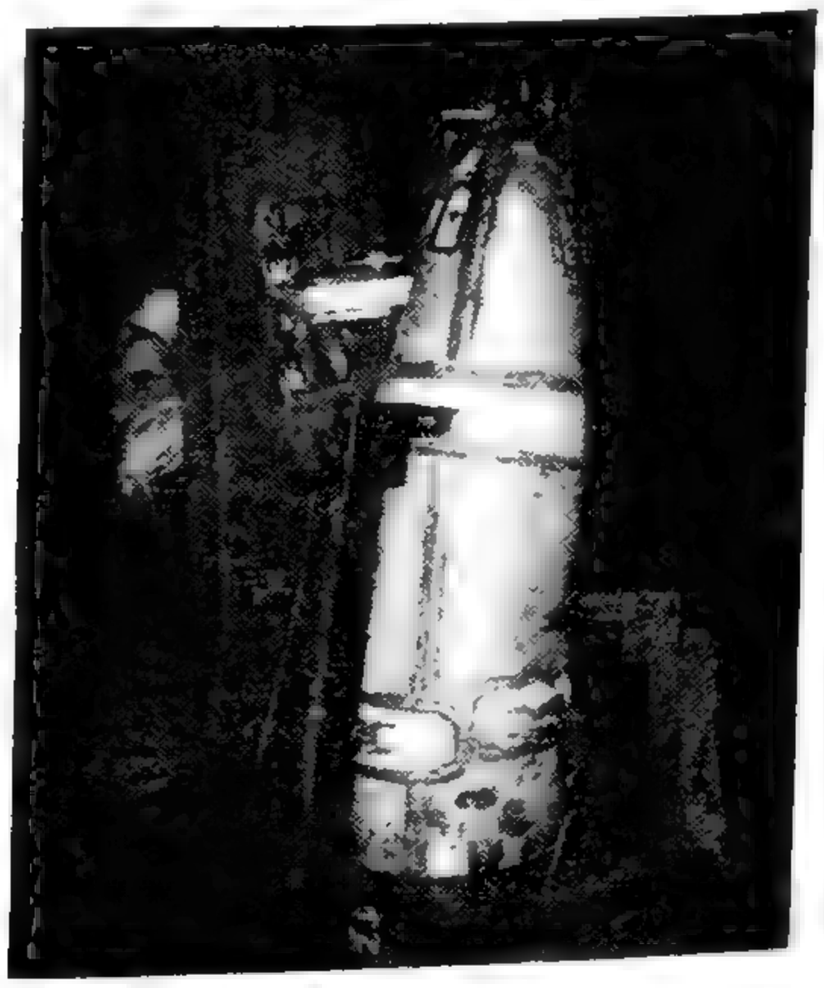


Fig. 20.—Jig for Arc Welding Tail-pipe Brackets

beveled to ensure full root penetration. Some assemblies lend themselves to setup by tack spot welding, which is an excellent method on low-carbon steel, aluminum or nickel alloys for setting up doublers or mating parts with outside flanges (see Fig. 21).

Thermal Treatments.—The use of thermal treatments such as preheat, controlled cooling and postheat treatment or stress relief varies according to the application and type of alloy. Low-alloy steels with no more hardenability than SAE 4130 are generally welded with little or no preheating and may receive a heat treatment after welding for increased strength. Steels with greater hardenability than SAE 4130 are used only if heat treatment tc produce a high strength after welding is required. These steels require preheating (preferably furnace) and controlled cooling to avoid cracking in or near the weld. Corrosion-resistant steel (18–8 type), if unstabilized, requires an annealing treatment after welding if maximum corrosion resistance is to be attained. In general, the stress relief of arc- and gas-welded assemblies is not practiced unless found necessary by repeated loading tests.

Defluxing.—Steels and nickel alloys are generally defluxed by light sand blasting. Magnesium is usually defluxed with hot water and manual scrubbing, followed immediately by a chrome-pickling operation. Aluminum alloys, by specification requirement, are defluxed with a 10% solution of sulphuric acid.

Flash Welding

Fit-up and Tolerances.—The dimensions of the clamping area play a very important part in the axial alignment and quality of flash welds. Misaligned abutting edges tend to slide laterally rather than upset properly and a poor bond results. To avoid this, the outside diameters of tubular members are usually held to a tolerance of about 0.005 in. for wall thicknesses up to 0.100 in., and held to 0.010 in. for heavier walls. (Cold finished tubing and bar stock is usually satisfactory without special sizing operations.) The usual length tolerance after welding is about $^1/_{32}$ inch. If a closer value must be held, this is obtained by machining after welding. Prior to welding, the details are held to a maximum length tolerance of $^1/_{32}$ in. each, so that

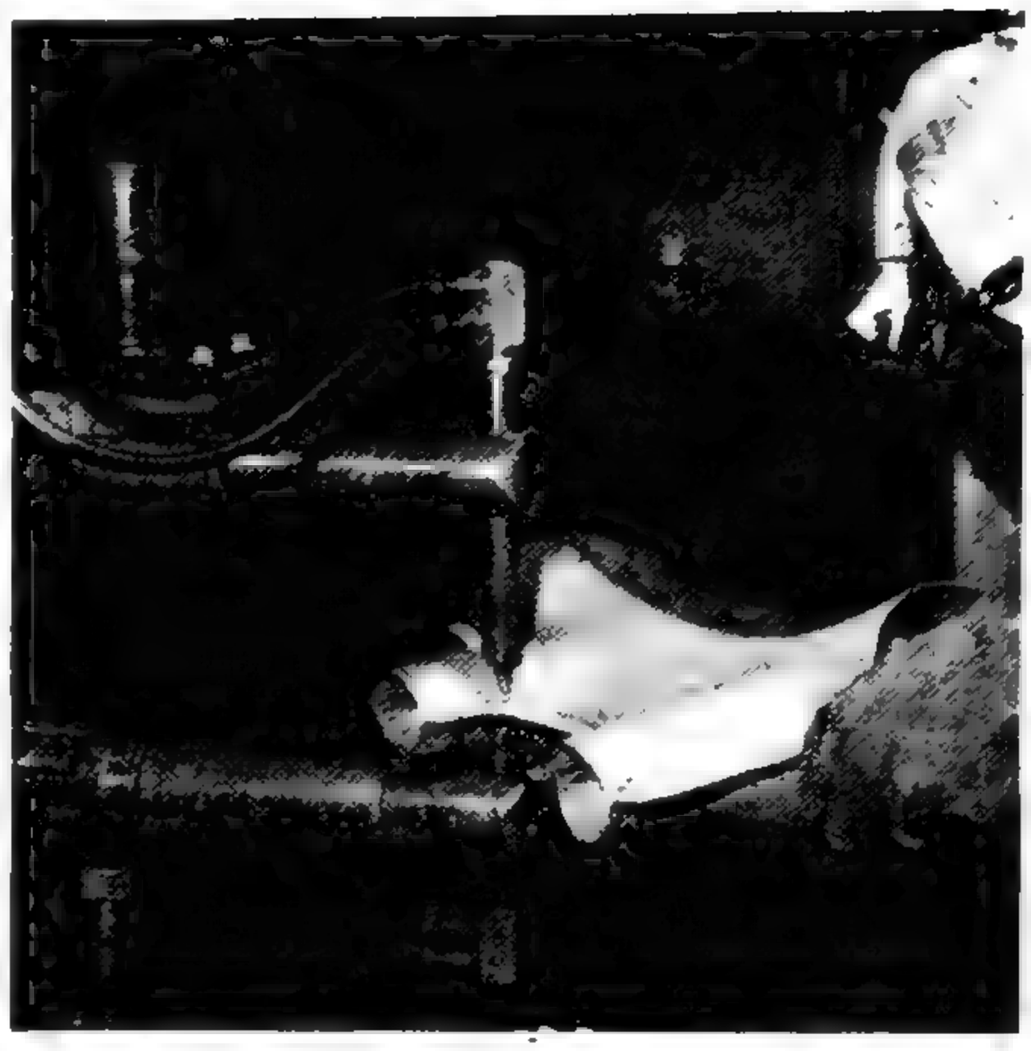


Fig. 21.—Tack Spot Welding of Type 347 Exhaust Manifold Section Prior to Arc Welding

the aforementioned final tolerance can be held without sacrificing weld quality.

Tooling.—Length dimension is usually maintained with the aid of back-up tooling. If the rotational relation of two end fittings is important, indexing pins may be incorporated into the back-ups. Such fixtures are frequently installed on the machine with the aid of a dummy part. Figure 22 shows a flash-welding machine with tooling designed to control rotation and length in welding a structural part.

Preparation of Parts.—All dirt, scale, grease and foreign material are removed from the clamping and welding areas. This practice ensures consistent welding and long die life.

Parts which must have the internal flash and spatter removed are usually masked internally with commercially available compounds and mechanical devices such as plugs made from copper, wood or cardboard.

Thermal Treatments.—The use of thermal treatments for stress relief alone is not generally practiced in aircraft applications of flash welding. Steels of hardenability great enough to be in danger of cracking due to the thermal stress of welding are invariably heat treated to a high strength value after welding. Cracking, if experienced, can usually be eliminated by placing the weldment in a furnace to control the cooling rate.

Protective Atmospheres.—Protective atmospheres have been found to be beneficial in the welding of heavy sections of low-alloy steel tubing. The gas is al-

lowed to flow on the inside of the tubing, and escapes at the joint during the flashing period. The thickness range in which the use of a protective atmosphere is beneficial has not been established, but appears to be $^3/_{16}$ in. and heavier. This probably will vary with each machine.

Two types of protective atmospheres have been used: the inert (argon or helium); and the reducing (a mixture of illuminating gas and hydrogen). Helium, being lighter than air, does not seem to blanket the weld as well as argon. The correct flow of either gas should be determined experimentally, since there is some evidence that an excessive flow may be detrimental to the weld. The illuminating gas-hydrogen mixture has been reported to be beneficial and to be less critical as to correct flow of gas than the inert gases.

Pressure Gas Welding

The essential considerations when using pressure gas welding are intimate contact of surfaces to be welded, heat, pressure and exclusion of air or any material that might cause physical or chemical discontinuity between the abutting weld faces.

The equipment necessary is a press of required capacity equipped with fixtures for holding the parts to be welded in alignment, an oxy-acetylene heating head and a device to measure and control the amount of *gather* (shortening of parts due to upsetting).

Figure 23 illustrates a hydraulic pressure gas welding machine together with the associated tooling and control equipment. The movable pressure plate at left is actuated by two hydraulic pistons that move in a plane through its center line. Such axial loading minimizes misalignment or angularity of the component parts.

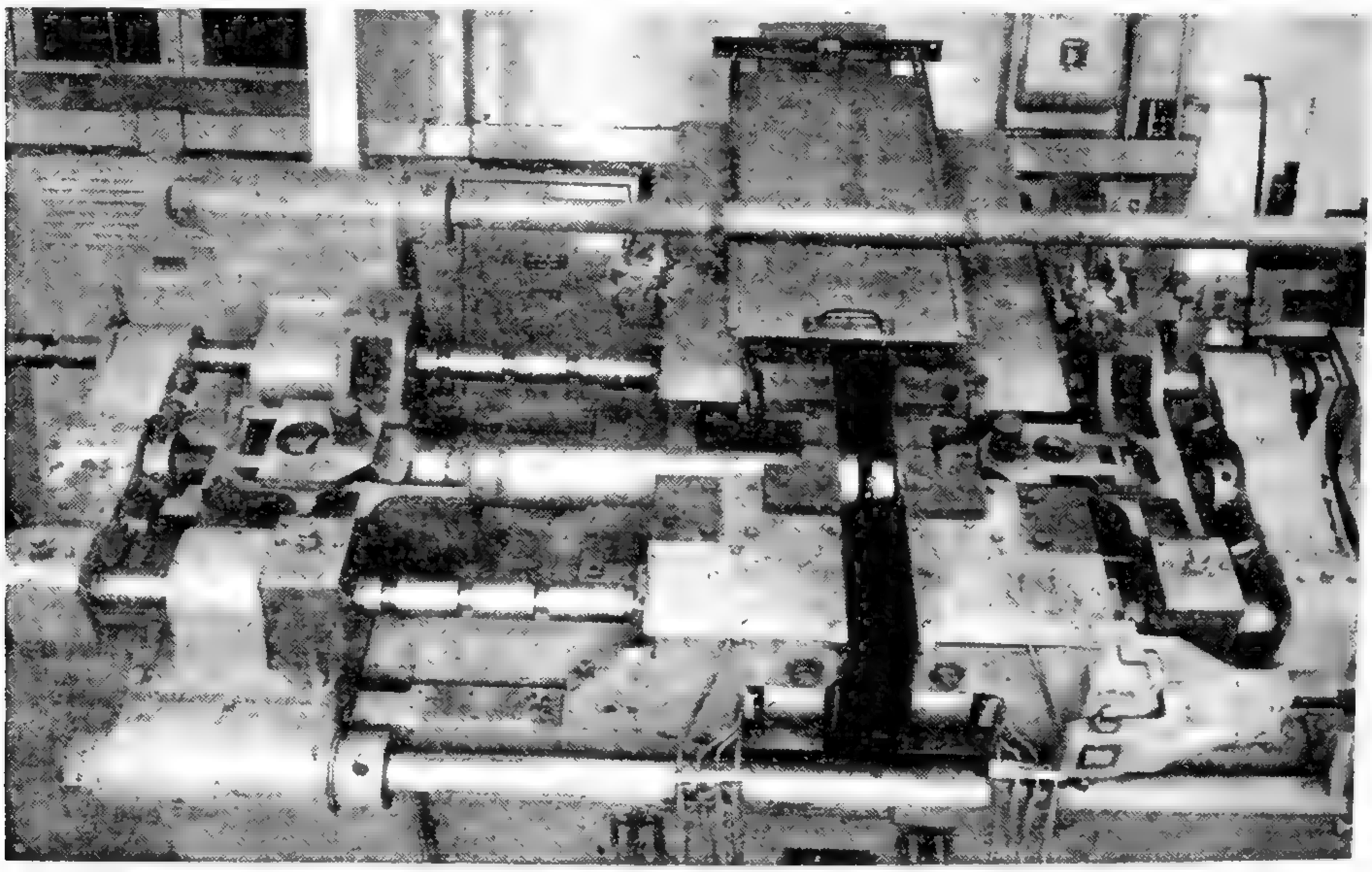


Fig. 22.—Locating Fixture and Flash-Welding Machine for Crew Nacelle Spar

Pins through forged clevis and tooling removed prior to welding.

The principal requirement of the heating head is that it produce a high temperature throughout the weld interface at a rate suited to the particular section. The heat gradient, both axially and radially, must also be considered so that weld faces do not open up because of differential thermal expansion. The heating head usually oscillates laterally or angularly so as to distribute the flame from each orifice over an appropriate area; this not only transfers heat efficiently but also prevents overheating of the metal beneath the flame tips.

The extent of upsetting can be effectively controlled by a limit switch to turn off the hydraulic pressure and fuel gas to the heating head simultaneously after the required amount of gather has taken place.

In practice, parts are machined with a good finish on the weld faces and firmly located in the welding machine by fixtures providing accurate alignment. All controls are set and the upsetting pressure is applied before the heating head is set. The heat, being concentrated at the weld plane, limits upsetting to a relatively small volume at the weld plane, until the gather control mechanism shuts off the heat and pressure. Welding time ranges from a few seconds to several minutes, depending on the wall thickness of the weld. An average time for a tube with $^1/_4$-in. wall thickness is about $1^1/_2$ minutes.

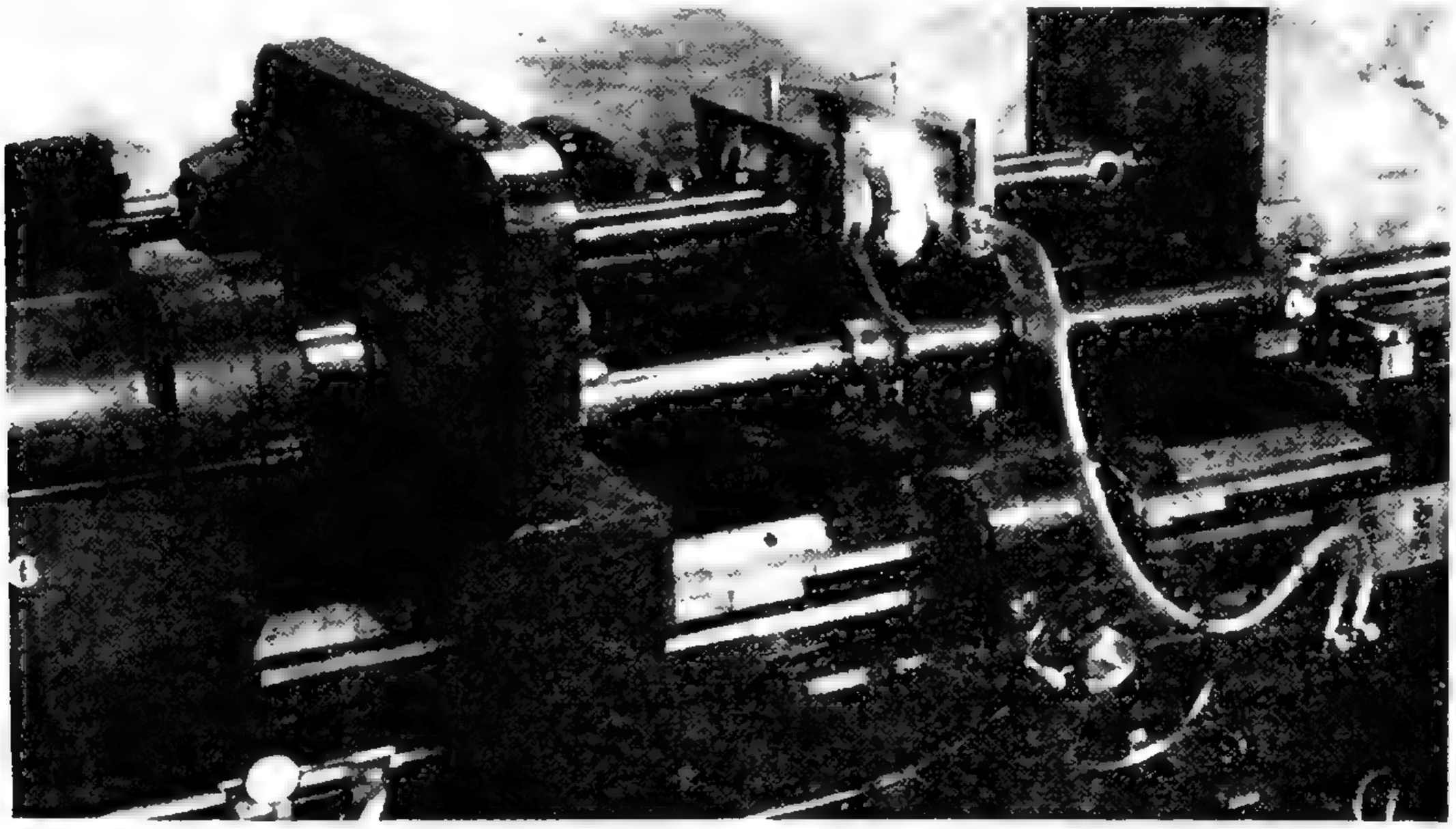


Fig. 23.—Pressure Gas Welding Machine for Aircraft Parts

Approximate maximum capacity is 50 sq. in. of weld.

Projection, Spot and Seam Welding

Fit-up.—Mating parts should be formed to fit so that no force other than light manual pressure is necessary to cause contact, and this should not tend to cause separation at other points.

Tooling.—Many parts are set up initially in jigs where they are either tack spot welded, fastened with a temporary device or riveted with a scattering of safety rivets (intended to prevent progressive failure of a row of spot welds). Riveting is generally used for aluminum and magnesium alloys, while tack spot welding with portable equipment frequently is used for steel assemblies. The tack spot welding may be accomplished by a *push gun*, where the electrode force is developed by the operator pushing the gun against the work, which in turn is backed up by either electrodes permanently located in the jig, or by an electrode held manually.

Better tack welds can be made using guns developing higher electrode forces. Such guns either lock into the setup fixture, or take the form of a yoke, with a device for developing a controlled electrode force through pneumatic, hydraulic or mechanical means. Such an operation is shown in Fig. 24. A third method of tacking consists of holding the jig with the parts in place up to a standard machine and making enough welds to locate the parts permanently. This is the only method of tack spot welding in general use on magnesium and aluminum alloys.

Portable Equipment.—Except for tack welding, very little aircraft work is done with portable equipment, and to date this has nearly all been confined to steel

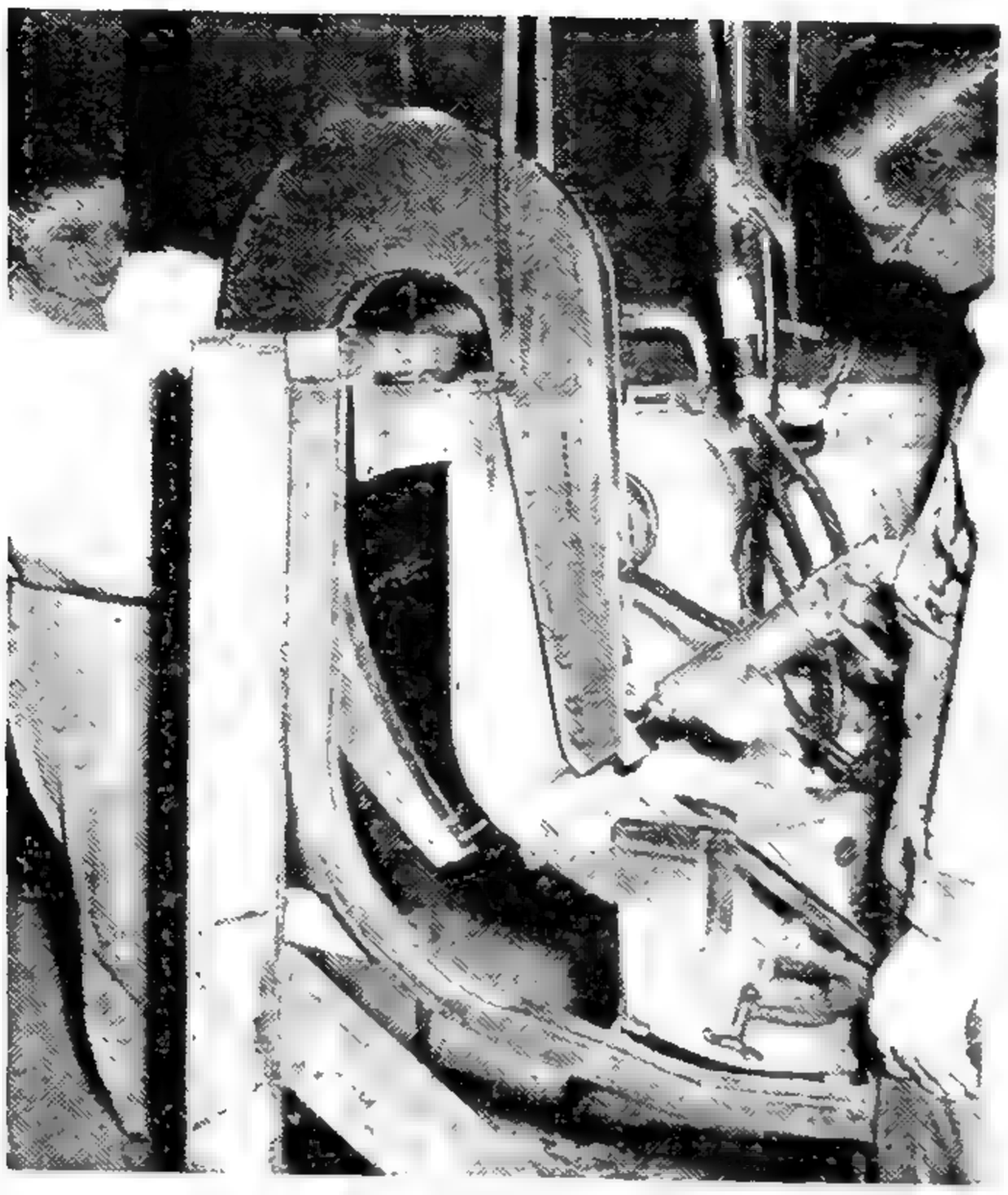


Fig. 24.—Tack Spot Welding Using Portable Gun

and nickel alloys. It is, of course, possible to maintain a satisfactory quality level with such equipment, and use has been made of it on continuously moving production lines, used during the war for high volume. Occasionally portable equipment is used to overcome a problem of accessibility. Such an application is shown in Fig. 25. In these cases, the assemblies at the time of welding were large and heavy, and the location of welding extremely confined, making it far easier to maneuver a gun than to position the assembly on a special setup in a welding machine.

Cleaning and Handling.—Steel and nickel alloys which are in a bright finish condition generally require no special cleaning prior to welding, other than the removal of oil, dirt, paint and foreign material. Steel with scale or oxides is usually pickled to remove those impurities.

Aluminum and magnesium alloys must have all surface impurities removed, including oxides as well as paint, oil, protective coatings and foreign material. There are many ways to accomplish this, and a number of commercial compounds are available. The result of considerable

Fig. 25.—Portable Spot-Welding Equipment for Hard-to-Reach Welds

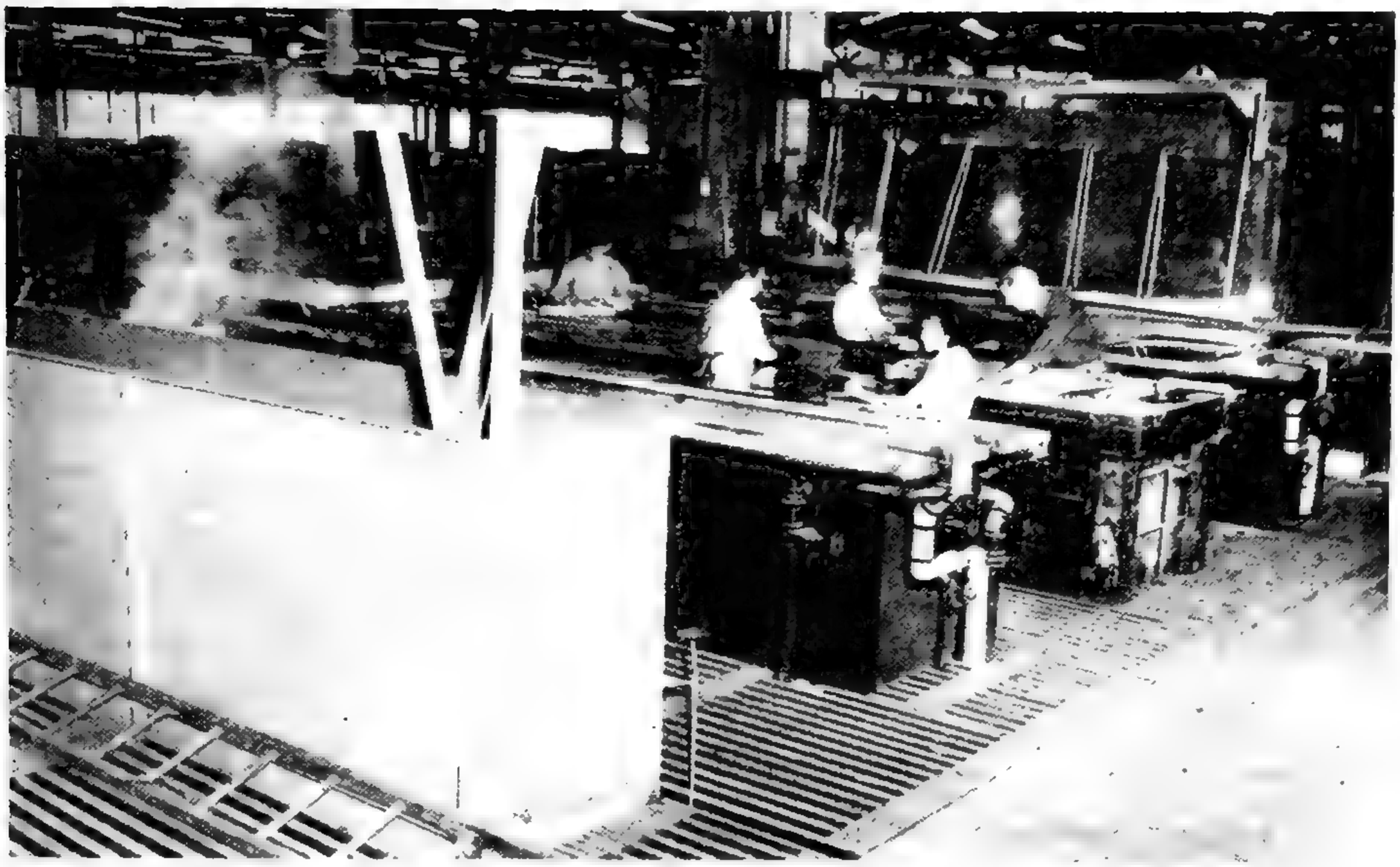


Fig. 26.—Cleaning Setup for Aluminum Alloys

research work has been reported.* Elaborate chemical tank installations are utilized for mass production preparation of aluminum alloys for spot welding. Figure 26 shows a cleaning and deoxidizing setup which uses hot alkaline cleaner, water rinse, hydrofluosilicic acid etch, water rinse and hot air drying, in that order from right to left. Aluminum and magnesium alloys should be welded as soon as possible after preparation since the greater the elapsed time, the greater the likelihood of contamination of the prepared surface. Of course, through mishandling, a carefully prepared surface may be contaminated, consequently every precaution should be taken to minimize the handling and time of exposure of the parts between preparation and welding.

Inert-Gas Metal-Arc Welding

Fit-up and Welding Fixtures.—Fit-up practices and welding fixtures are not appreciably different from those of other arc- and gas-welding processes. Tack spot welding is an excellent method for holding the details together prior to the welding operation for lap or flanged butt joints.

Shielding, Fluxing and Deoxidizing.—Argon is the gas more commonly used for shielding in aircraft work. The flow is set at about 5 liters per min. for corrosion-resistant steels or nickel alloys, at about 10 liters per min. for aluminum and 3 liters per min. for magnesium alloys.

Corrosion-resistant steels and nickel alloys are usually fluxed on the back side. Aluminum alloys require no flux, using the procedures recently developed. The elimination of flux on aluminum is especially advantageous, since satisfactory defluxing is difficult and expensive.

The surface of aluminum alloys is generally prepared for welding using the same procedures as for spot welding. Since this is generally a mass production technique, it adds little to the cost of the process, but contributes much to the soundness of the weld.

Brazing

Steel, Furnace Brazed with Copper.—Furnace brazing with copper for aircraft production parallels practices in use in other industries for carbon and low-alloy steels, although stringent quality requirements and emphasis on strength necessitate the following additional considerations:

1. Cleaning. Scale, paint and other foreign matter must, of course, be removed. Following this, cleaning with

* See Bibliography.

solvent is desirable to remove all remaining traces of surface contaminants. Foreign matter, although small in quantity, may cause imperfections not otherwise undesirable but unsuitable for aircraft. Trichloroethylene vapor degreasing solvent appears best although satisfactory results are reported with petroleum solvents and alkaline-type cleaners.

2. Soaking Periods vs. Mechanical Properties. From an economy standpoint, the time in the heating chamber of the brazing furnace (soaking period) should be reduced to a minimum. The longer parts remain in the heating chamber, the lower the total brazing capacity of the furnace.

In addition, for the same cooling rate, the tensile and yield properties in the as-brazed condition developed after heating to 2100°F. decrease as the time at that temperature increases. Simultaneously elongation and reduction of area increase. These changes result partly from decarburization and partly from change in the grain size, although the first cause is more prominent. In actual design and production, increased grain size and the resulting reduction of impact values, as measured by a notched specimen such as the Charpy, are of relatively small significance. Few as-brazed aircraft parts are subject to impact, these being confined mainly to gun or bomb equipment. Aircraft applications subject to impact are usually accompanied by high loads and, consequently, hardening by heat treatment subsequent to brazing is required. The hardening treatment automatically refines the grain and increases the resistance to impact.

3. Decarburization. Unlike the brazing of low-carbon steel parts in which carbon content is relatively unimportant, the loss of carbon from low-alloy steels (e.g., SAE 4130) in the copper furnace brazing heating cycle destroys the hardening properties on the surface of the material. In thin gage material or thin wall tube, this may result in appreciable loss. Where the water and carbon dioxide content of the furnace atmosphere are not controlled, decarburization to a depth of 0.020 in. can readily result. In a 0.060-in. wall tube, for example, the total decarburization would amount to 0.040 inch. Assuming the tube to be heat-treated to 160,000 psi. and using 45,000 psi. as the strength of the decarburized area, the strength loss is about 48%. Decarburization limits of 0.005 to 0.010 in. are desirable, so that the resulting strength loss will not exceed that occasioned by normal heat-treating practice. This can be accomplished by control of water and carbon dioxide in the atmosphere generating system, the plugging of leaks in the furnace, adjustment of the flame curtains at the furnace loading openings and by continuous 24-hr. operation.

4. Fluxing. Steels with large quantities of alloying constituents, such as corrosion-resistant steel (18–8), require the use of flux to accomplish a satisfactory bond.

5. Jigging. Self jigging, to prevent shifting of the parts during brazing is generally practiced. Staking, spot welding, pinning or tack welding are the methods commonly employed.

Steel, Silver Alloy Filler Metal.—Four brazing processes are used with silver brazing alloys in aircraft production. They are torch, induction, furnace and resistance (incandescent carbon) brazing, probably of importance in the order named.

1. Cleaning, Fluxing and Addition of Filler Metal. Scale, oxides, paint and grease must be removed from the parts and filler metal prior to brazing. Both the parts and filler metal are fluxed. For torch brazing, temperature is judged by color and flux melting, and the filler metal is applied as needed for complete penetration of the joint and the formation of fillets. For all other processes, the parts are fluxed and wire or strips of alloy are preplaced before brazing. After brazing the parts are defluxed as soon as possible, usually with hot wtaer.

2. Jigging. Parts joined by torch, induction or furnace brazing usually require jigging. The jig must be made of materials adequate to withstand any heat which may be encountered, and if it is to be exposed to the magnetic field of the induction machine, should be of non-magnetic materials. The jig must be designed so that the parts are in a suitable position for gravity to assist and equalize the flow of the brazing alloy to all parts of the joint. Too rigid jigging, which restricts expansion and contraction of the parts, may result in a poor bond.

In resistance brazing hardened electrical connectors, special fixtures to prevent overheating and annealing the entire connector must be used.

Aluminum.—Torch, furnace and dip brazing are used.

1. Cleaning, Fluxing and Addition of Filler Metal. Parts should be free from grease, paint, dirt, heavy oxides, etc. Flux should be applied directly to

the joint, and, for torch brazing, to the filler metal. The filler metal for furnace or dip brazing must be preplaced.

2. *Jigging.* Jigs may be used to hold the parts for both torch and furnace brazing. Self jigging is generally used for dip brazing and has application for other heating methods as well.

Soft Soldering

Soldering performed on aircraft electrical systems must be done with a rosin-type flux to avoid the possibility of subsequent corrosion. Usually an electric iron is the source of heat, although occasionally torch or carbon resistance heating is employed.

Soldering for other applications is generally done with the aid of an acid-type or a zinc-ammonium-chloride flux and a gas torch. Care must be exercised in manipulating the torch to avoid overheating the parts. Most parts are pretinned prior to soldering with the aid of small electric solder pots. Defluxing with a mild caustic solution is recommended after soldering is completed, when an acid-type flux has been used.

QUALITY CONTROL

Arc and Gas Welding

*Welder Certifications.**—The welder using any of the arc- or gas-welding processes must pass a certification test before he is permitted to weld production parts. He is retested every six months, or oftener if there is doubt of his ability.

For the purpose of the tests the alloys used in aircraft are divided arbitrarily into five groups, as follows:

Group I—Carbon and Alloy Steels
Group II—Corrosion-Resistant Steels
Group III—Copper and Nickel Alloys
Group IV—Aluminum Alloys
Group V—Magnesium Alloys

In the case of Group I, there is an additional breakdown into Classes *A* and *B*. *Class IA* welders are permitted to weld any parts within Group I; *Class IB* welders are limited to non-structural welding.

The test consists of the joints shown in Fig. 27 and the requirements shown in Tables 11 and 12.

Procedure Control.—The following factors are important to proper control of the welding procedures:

1. *Design.* Good design is important both for quality and production. Frequently it is necessary to correct design for the general improvement of one or the other factor as decided by the welding engineer, who should be consulted on all design matters.

2. *Fit-up.* Good fit-up is very important if good welding is to be obtained. This phase is controlled jointly by the welder (who will be blamed for poor welding) and the welding engineer (who should control design and shop practice).

3. *Welding Sequences.* Complicated parts sometimes require specially developed welding sequences in order to ensure good quality. These sequences are written up as welding procedures by the welding engineer, and should be followed by the shop personnel.

4. *Welder Identification.* Each welder is issued an identification stamp to use on his work. Records are required (by specification) showing the relative proficiency of each welder. It is left to the individual contractor to determine the form of such records. Their purpose is to aid in improving quality through corrective educational action, or stronger action if necessary.

Inspection of Weldments.—The following inspection methods, which are discussed in detail in Chapter 42, Inspection, are applicable to aircraft fabrication:

1. *Magnetic Inspection.* Weldments made from magnetic materials such as carbon and low-alloy steels may be examined by magnetic particle inspection. This inspection must be performed by certified personnel on approved equipment, in accordance with Specifications AN-I-32 and AN-I-39.

2. *Fluorescent Penetrants.* Another inspection method, independent of magnetism but dependent upon the defect extending to the surface, utilizes a fluorescent penetrant which soaks into the defect. When the part is later inspected under *black* light, the defect, if present, is outlined by the fluorescent material. This process is governed by Specification AN-I-30.

3. *Radiographic Inspection.* This inspection method is applicable to any of the alloys used in weldments for aircraft. Its limitations are caused by the shape of the weldment, sometimes making it difficult to get a sharp picture. This inspection method is governed by Specifications AN-I-26 and AN-X-2.

4. *Visual Inspection.*—Welds on aircraft parts are required always to pre-

* See Specification AN-T-38.

Table 11—Tests Required for Aircraft Welder Certification

Group	Original	Semi-Annual
IA	Joint 2, Horizontal, Overhead Joint 2, Vertical, Overhead Joint 3, Bench[a] Joint 4, Bench[a]	Joint 4, Bench[a]
IB	Joint 1, Bench[a] Joint 2, Horizontal, Bench Joint 2, Vertical, Bench Joint 2, Horizontal, Overhead Joint 2, Vertical, Overhead	Joint 2, Vertical, Overhead Joint 2, Horizontal, Overhead
II, III, IV or V	Joint 5, Thick, Bench[a] Joint 5, Thin, Bench[a] Joint 6, Bench[a] Joint 7, Bench[a]	Joint 5, Thick, Bench[a] Joint 5, Thin, Bench[a]

[a] Positioned to suit the welder.

sent a workmanlike appearance equal to that which would be acceptable for welder qualification tests.

5. Physical Tests. Tanks, exhaust stacks and air ducts are frequently inspected by application of internal air pressure and immersion in water (or covering with a bubble solution) for the detection of leaks. Important parts are sometimes proof tested in tension, compression or bending.

Flash Welding

Equipment Qualification.—Details for qualifying flash-welding machines and certifying settings are prescribed in Specification AN-W-31. Briefly, the tests for new equipment include 15 welds each for the greatest, least and one intermediate section to demonstrate the consistency of operation of the equipment. The welded

Table 12—Minimum Requirements for Aircraft Welder Certification

Joint No.	Requirements
1. Butt joint in plate	Appearance: Little warpage, sound welds Strength as-welded; tension, psi.:

Carbon Content of Filler Metal, %	Carbon Steel Base Metal	Alloy Steel Base Metal
0.06 and below	45,000	55,000
0.07 to 0.12	50,000	65,000
over 0.12	55,000[a]	70,000[a]

Joint No.	Requirements
2. Butt joint in tubing	Appearance: Sound weld, total weld bead thickness not more than twice tube wall. Strength as-welded, tension: Carbon steel—50,000 psi. Alloy steel— 80,000 psi.
3. Vertical Fillet Weld	Appearance: Fillet size, legs to be ½ in. maximum. Sound weld, 100% weld root penetration. Strength as-welded, tension: Carbon steel—10,000 lb./linear inch Alloy steel— 15,000 lb./linear inch
4. Cluster	Appearance (external and etched section): Sound weld, 15% minimum penetration into plate, complete root penetration.
5. Butt joint in sheet	High ductility base metal: Bend through 180 deg. around a diameter equal to twice the sheet thickness; total length of all cracks must be less than 1/16 in. Low ductility base metal: Radiographs to show sound metal. Tension tests to show sound metal.
6. Tee Joint in Sheet	External appearance and section and etch: Sound weld, satisfactory penetration, little warpage.
7. Simulated difficult production part	External appearance: Good. Section and etch: Sound weld, good penetration.

[a] Required for alloy steel filler metal.

NOTE: Soundness of a weld is judged by freedom from defects such as poor root penetration, excessive burn-through, poor shape of weld bead, undercutting, overlapping, slag inclusions, cracks and porosity.

specimens are tested to destruction in tension or bending. Graphs must be prepared to aid in establishing other intermediate settings.

Procedure Certification.—For settings not previously certified, the test consists of five welds. However, should any of the five fail, 15 welds are then necessary to qualify the setting. These welds are tested to destruction by bending or in tension.

Specimen Preparation.—The test specimens consist of simulated or actual production parts. All joints must be normalized or heat treated prior to testing, the final condition of the test specimens being equal to or nominally stronger than the parts they represent. If whole welds are tested, each must equal or exceed 95% of base metal strength. Welds too large to be tested are cut into strips and all strips tested. The average strength of the strips must be 95% or more of the base metal and no single strip must drop below 80% except that occurrence of a single test value not lower than 60% is acceptable provided the previous history of tests for the particular setting involved indicates no frequency of occurrence of this low value greater than 1%. No de-

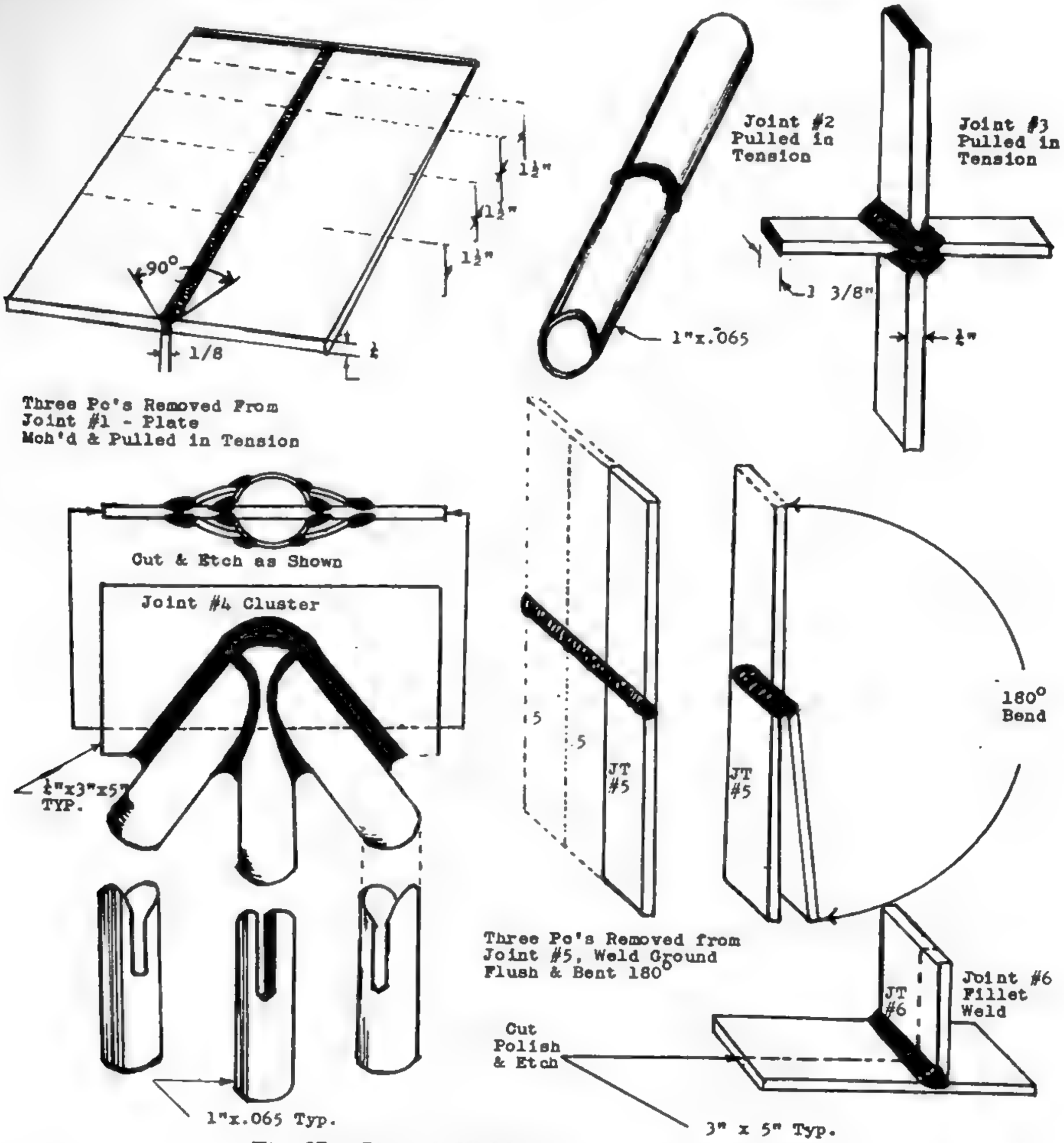


Fig. 27.—Aircraft Welder Certification Test Joints

fects commonly associated with faulty welding can be present in acceptable test specimens.

Quality Standards.—No visible defect, such as cracks, inclusions, die burns or porosity, is acceptable on a production part. Misalignment of the thickness at the plane of the weld of sheet or tubing cannot exceed 0.008 in. or 10% (up to 0.030 in.) whichever is larger. For bars, 5% of the diameter is the limit. Angular misalignment must not exceed 0.010 in. per inch of length up to a maximum of 0.030 inch.

Production Quality Control.—All production parts and tests representing such parts must be welded in accordance with a certified procedure. Each time the machine is set up for a production run, three or more welds are made and tested to destruction. (Where 100% proof testing of production parts is practiced, destructive testing of large sections may be waived.) This test must demonstrate that the machine is functioning satisfactorily before production welding is started.

Inspection of Finished Parts.—Inspection methods used include magnetic particle inspection, physical testing and radiography. Magnetic inspection must be used with caution, since the change in hardness (and permeability) and a change in section give rise to indications of defects which do not exist. Radiography is difficult to apply, and not extensively used.

Two types of physical tests are used. First is the destructive testing of coupons representing each lot of parts (or the destructive testing of parts). Second is the proof testing of welds to a value just below their yield strength (67% or more of ultimate), applied to a percentage of the parts, varying from a few to all in a lot. Records of the results of the physical tests are kept, and if no rejections are experienced, they are sometimes discontinued. All parts are checked for proper dimensions, external welding defects such as die burns, proper upset appearance and proper flash removal, straightness and alignment of the weld.

Pressure Gas Welding

Procedure Certification.—Inasmuch as the final goal is a weld just as strong as unwelded material, emphasis is placed on the development of proper machine settings. For every weld size that is to be made, a set of metallurgical and bend specimens is prepared. The purpose of metallurgical specimens is to evaluate the quality of welds by microscopic examination. The trial specimens are welded according to empirical data and sectioned to determine metallurgical characteristics which can be interpreted in terms of possible physical properties. The various points determined by the examination are the depth of fissure, if present, and the amount the fissure propagates in heat treatment, depth and intensity of oxygen rich areas, amount of melting of outside diameter, depth of intergranular penetration, and the amount of belling or flaring of the tube outward at the weld.

If, after metallurgical examination, approval of the weld is secured, full-size, static bend test specimens are welded under the same conditions as was the approved metallurgical specimen. Heat treatment by normalizing, quenching and drawing to 180,000 to 220,000 psi., plus machining in the same manner as used for the actual structural part, follows.

The welds are then statically bend tested and evaluated. Results of the bend tests govern whether or not the finished parts can be welded using the same machine settings as were used for the bend specimens.

Inspection.—Inspection of finished parts is accomplished visually and by magnetic particle analysis, mechanical tests or radiography as applicable.

Projection, Spot and Seam Welding

General.—Aluminum and magnesium spot and seam welding quality control procedures and requirements are to be found in detail in Specification AN-W-30. Similar information for nickel alloys and steels, is to be found in Specification AN-W-32. These specifications provide for qualification tests on equipment, certification tests for welding procedures and finally stipulate minimum quality requirements which are sufficiently rigid to ensure the adequate serviceability of a part if it is properly designed. Surveys conducted by radiographic means on aircraft production parts in aluminum alloys showed that few of these contained spot welds which were entirely free from defects. However, aircraft spot welding is at all times maintained at the highest quality level the design of the parts and

the shop handling procedure will permit, consequently very few service failures have been experienced.

Spot Weld Strength Requirements.—Table 7 lists the maximum permissible design strength (lb. shear) for spot welds. In order to avoid any likelihood of weld failures, the Government specifications require spot weld quality in aluminum and magnesium alloys to be maintained at 1.25 times the specified values of Table 7. To accomplish this the average strength based on a sample size of three must be not less than 1.56 times, and, based on a sample size of twenty, 1.66 times the respective applicable values in Table 7. Complete tables giving the detailed strength requirements are to be found in the Government specifications previously mentioned.

Procedure Certification.—In the case of projection, spot and seam welding, great emphasis is placed on the establishment of reliable settings for each particular joint and each particular machine. Details of the procedures for this purpose are found in the Government specifications. Both shear and macrosection specimens are required for spot welding; seam welding is frequently checked utilizing pressure coupons; projection welding is checked by destructive tests and macrosections on production parts or coupons. These tests must indicate adequate strength and relative freedom from objectionable defects. Test coupons frequently used are shown in Fig. 28. Records of all tests must be maintained.

Production Routine Testing.—Routine tests during the course of production, but not so detailed as those used for setting certification, are employed to demonstrate that the level of quality of the production parts is adequate. If an approved form of statistical control is utilized, the amount of testing may be reduced to a minimum. Complete records of these tests must be maintained. (See Chapter 44 for further information on statistical control.)

Inspection of Weldments.—The completed weldments are inspected visually for workmanship. Joints which are important from a safety standpoint may be checked radiographically. To be acceptable the assembly must be of the highest quality possible, consistent with the design and service requirements for the part.

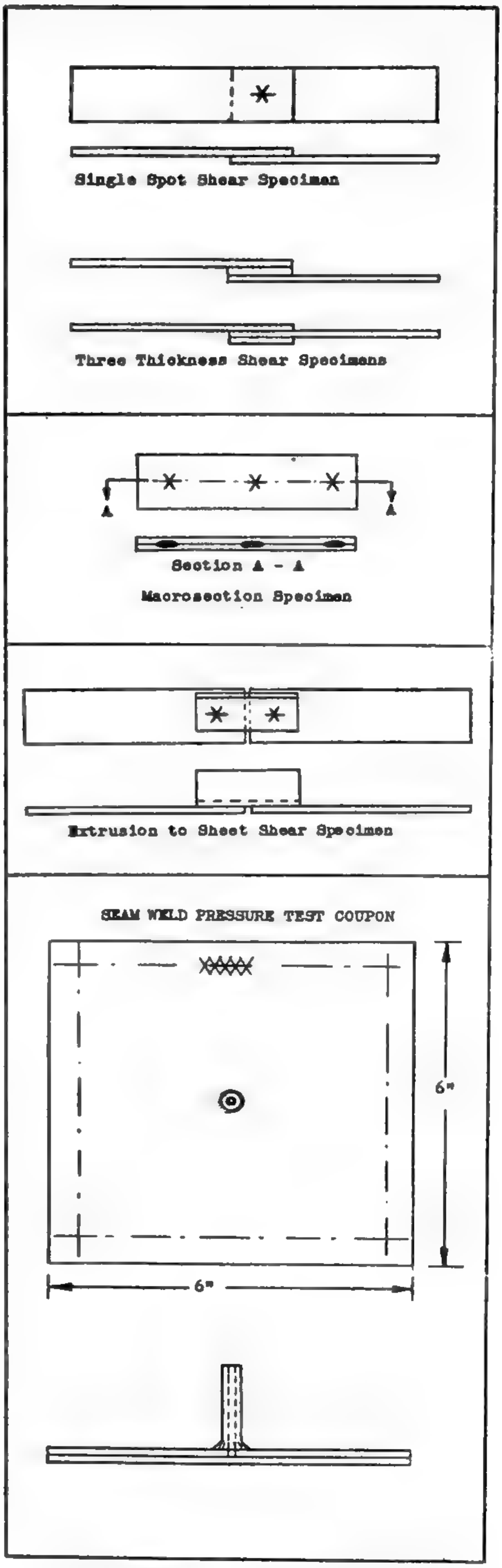


Fig. 28.—Spot and Seam Welding Test Specimens

An excellent discussion of radiography as applied to spot welds will be found in some of the articles listed in the bibliography.

Maintenance of Equipment.—Probably equally important with workmanship in its contribution to consistent quality is proper maintenance of the equipment. All relays and contactors need to be kept in first-class condition. The cooling system must be kept clear of obstructions so that the coolant may flow freely through it. All connections in the secondary circuit must be kept tightly bolted and polished at regular intervals with abrasive cloth. Air cylinders must be provided with constant lubrication and all other moving parts must be lubricated at regular intervals.

For the complex machines used to weld aluminum or magnesium, a recording oscillograph with several channels and the auxiliary equipment for recording, simultaneously, electrode force and current is an almost indispensable tool. With the aid of such a device, trouble is quickly located and after repairs are made, the dial readings can be adjusted so that previously established settings are still valid.

A discussion of equipment of this kind and its use will be found in some of the articles listed in the bibliography.

Brazing

Operator Qualificaton.—In torch or induction brazing, operator skill can definitely influence the strength of the joint. Consequently, in many cases an operator certification test is required. Frequently this test consists of brazing specimens of the plug and ring type which are tested to determine the tensile strength of the joint and examined for areas not brazed.

Procedure Control.—The best assurance of a good bond is the rigid adherence to the design requirements and the procedures previously specified.

A well-trained operator who carefully follows a proper procedure will nearly always produce a sound joint.

Inspection Methods.—Formerly, inspection requirements specified that 100% bond be secured in copper furnace brazed aircraft parts. Macrosections were made of one or more parts representative of the lot. In this examination, "joints not completely filled with brazing material; dirt or flux at the joints; or excessively wide gaps in the joints" were causes for rejection. While such a requirement was, of course, subject to liberal interpretation, the concept of perfect bond did not recognize the variations which exist in a production-type process. Current inspection techniques are based on three considerations:

1. Where possible, the brazing alloy is placed at one end of the joint and allowed to flow through to the opposite end. This method not only prevents the entrapment of gas on the interior of the part, but permits visual examination for a fillet at the opposite end of the part to indicate complete copper penetration.
2. Visual examination is made for a bond complete at all edges and recessed not more than 15 to 20% of the joint width.
3. Where visual inspection indicates questionable joints, non-destructive or destructive tests of representative samples are made to demonstrate that the defective areas of the joints do not exceed 15 to 20% of the total area required to be bonded.

The above technique and quality standards, while providing a high quality level, permit small variations inherent with brazing. The presence of a safety factor of 1.6 between the minimum strength expected in a perfect bond (25,000 psi. or above) and the allowable design strength (15,000 psi.) amply provides for strength loss sustained by the presence of any defects.

BIBLIOGRAPHY

Governing Specifications and Codes

Welder Certification:

Test; Aircraft Welding Operators' Certification: AN-T-38

Filler Metal and Flux:

Electrodes, Mild and Alloy Steel Welding: AN-E-9

Electrodes, Welding (Covered), Copper-Aluminum-Iron Alloy (Aluminum-Bronze) (For Surfacing): JAN-E-278

Electrodes, Welding (Covered), Corrosion-Resisting (Austenitic Type) Steel: BuAer 46E4 (Int)

Electrodes, Welding (Covered), Nickel-Copper Alloy: BuAer 17E4

Nickel-Chromium-Iron Alloy Wire and Welding Rod: AN-N-4

Rods, Welding (Nonferrous), Gas Welding: Fed. QQ-R-571
Solder, Brazing (Copper-Zinc): 46S 15, Fed. QQ-S-551
Solder, Silver: Fed. QQ-S-561
Solder, Tin, Lead: Fed. QQ-S-571
Solder, Tin-Antimony: BuAer 46S38
Solder, Lead-Silver: AN-S-59
Solder, For Use on Aluminum Alloy: S-134
Flux, Magnesium Alloy Welding: AN-F-44
Flux, Gas Welding for Aluminum and Aluminum Alloys: AN-F-57
Flux, Gas Welding for Corrosion and Heat-Resistant Steel: BuAer 51F3, AAF 11314
Flux, Gas Welding for Nickel-Chromium-Iron Alloys: BuAer 51F7, AAF 11315
Flux, Brazing, Silver Alloy: BuAer 51F4, AAF 11316
Flux, Soldering (Paste): BuAer 51F1
Fluxes, Welding, for Copper and Nickel Base Alloys and Cast Iron: BuAer 51F8 (Int)
Wire, Iron and Steel; Welding (For Aeronautical Use): BuAer 46R4, AAF 10286
Rod, Welding, Chrome-Cobalt-Tungsten Composition for Hard Facing Metal Parts: BuAer 46R5, AAF 10300
Rod, Zinc Alloy, Welding (for Aeronautical Use): AAF 10302
Rod, Magnesium Alloy, Welding: AN-R-25
Rods, Nickel-Chrome-Boron Alloy Welding: BuAer R-41
Rods, Welding, Aluminum and Aluminum Alloy (for Gas Welding): BuAer 46R7
Rods, Welding, Nonferrous, Copper and Nickel Base Alloy (for Gas and Carbon Arc): BuAer 46R1
Rods, Welding (Oxy-acetylene), Steel (Corrosion Resisting, 18-8 Type) (Columbium Bearing), (Aircraft Use): BuAer 46R2
Rods, Welding, Tungsten Carbide: BuAer 46R3

Process and Inspection Methods:

Brazing, Aircraft Parts: AAF 98-20003
Brazing Process Furnace, Copper, for Aircraft Parts: AAF 20018
Brazing, Silver Solder, Process for: AAF 20019
Welding, Flash, Butt, General Specification for: AN-W-31
Welding, Magnesium: BuAer PW-2
Welding, Aluminum: BuAer PW-5
Welding, Steel: BuAer PW-7
Soldering Process, General Specification for: AN-S-62
Inspection, Radiographic: AN-I-26
Inspection Process, Magnetic Particle: AN-I-32
Inspection Requirements, Magnetic Particle: AN-I-39
X-Ray Laboratories, Procedure for Certification of: AN-X-2
Inspection, Fluorescent Penetrant, Method of: AN-I-30
Welding, Aluminum and Magnesium Alloys, Spot and Seam: AN-W-30
Welding, Low Carbon Steels, Austenitic Steels, and Nickel Alloys, Spot and Seam: ANW-32
Welding, Spot, Hardenable Steels, General Specifications for: USAAF 20011-E

Standards, Articles and Books

1. *Tentative Standards and Recommended Practices and Procedures for Spot Welding of Aluminum Alloys*, American Welding Society, 1942.
2. *Welding in the Aircraft Industry*, Northrup Aircraft (for the Aircraft War Production Council), 1943.
3. *Summary of Observations of Cracking in Spot Welds in Alclad 24S-T*, R. A. Wyant, The Welding Journal Res. Suppl., March 1945.
4. *Spot Weld Characteristics of Heavy Gages of 24 S-T Alclad Aluminum Alloy*, M. L. Ochiano, The Welding Journal Res. Suppl., March 1945.
5. *Determination by Statistical Analysis of Process Minimums for Spot Welding*, Harold Robinson, The Welding Journal, May 1945.
6. *Investigation of the Final Rinsing Operation in the Chemical Surface Preparation of Alclad 24S-T for Spot Welding*, R. A. Wyant, D. J. Ashcraft and T. B. Cameron, The Welding Journal Res. Suppl., July 1945.
7. *An Investigation of the Spot Welding of Aluminum Alloys Using Condenser-Discharge Equipment*, W. F. Hess, R. A. Wyant and B. L. Averbach, The Welding Journal Res. Suppl., August 1945.
8. *Instrumentation of the Spot Welder and Investigation of the Spot Welding of 0.091-In. to 0.091 In. 24S-T Alclad Sheet*, R. C. McMaster and N.A. Begovich, The Welding Journal Res. Suppl., October 1945.
9. *The Spot Welding of N.E. 8715, N.E. 8630 and S.A.E. 4130 in the 0.125-In. Thickness*, W. F. Hess, W. D. Doty and W. J. Childs, The Welding Journal Res. Suppl., October 1945.
10. *The Spot Welding of Dissimilar Thicknesses of Alclad 24S-T*, W. F. Hess, R. A. Wyant and B. L. Averbach, The Welding Journal Res. Suppl., December 1945.
11. *Spot Welding of Heavier Gages of Aluminum Alloys, Parts II and III*, R. C. McMaster and N. A. Begovich, The Welding Journal Res Suppl.. December 1945.
12. *Strength of Aircraft Elements*, AN-C-5, 1946.
13. *An Investigation of Current-Wave Form for Spot Welding Alclad 24S-T, 0.020 In. in Thickness*, W. F. Hess, R. A. Wyant and B. L. Averbach. The Welding Journal Res. Suppl., January 1946.
14. *The Spot Welding of N.E. 8715, N.E. 8630 and S.A.E. 4340 in the 0.62 In. Thickness*, W. F. Hess, W. D. Doty and W. J. Childs, The Welding Journal Res. Suppl., February 1946.
15. *Tension Tests of Single-Row Spot-Welded Joints in 24S-T Alclad Aluminum Sheet*, R. Della Vedowa, The Welding Journal Res. Suppl., February 1946
16. *The Surface Preparation of Aluminum Alloy Sheet for Spot Welding*, R. A. Wyant, D. J. Ashcraft, T. B. Cameron and K. H. Moore, The Welding Journal Res. Suppl., February 1946.
17. *An Investigation of Electrode Pressure, Cycles and Current Wave Forms for Spot Welding Alclad 24S-T*, W. F. Hess, R. A. Wyant, B. L. Averbach and F. J. Winsor, The Welding Journal Res. Suppl., March 1946.
18. *Some Observations of Spot Weld Consistency in Aluminum Alloys*, W. F. Hess, R. A. Wyant, B. L. Averbach and F. J. Winsor, The Welding Journal Res. Suppl., April 1946.
19. *An Investigation of the Effect of Spot Welding on the Sheet Efficiency of Aluminum Alloy 24S-T*, W. F. Hess, R. A. Wyant and F. J. Winsor, The Welding Journal Res. Suppl., May 1946.
20. *An Investigation of the Fatigue Strength of Spot Welds in the Aluminum Alloy Alclad 24S-T*, W. F. Hess, R. A. Wyant, F. J. Winsor and H. C. Cook, The Welding Journal Res. Suppl., June 1946.
21. *The Spot Welding of Multiple Thicknesses of 0.040 In. Alclad 24S-T*, W. F. Hess, R. A. Wyant and F. J. Winsor, The Welding Journal Res. Suppl., July 1946.
22. *Further Investigation of the Effect of Spot Welds on the Sheet Efficiency of Alclad 24S-T*, W. F. Hess, R. A. Wyant and F. J. Winsor, The Welding Journal Res. Suppl , July 1946.
23. *The Spot Welding of Ten Aluminum Alloys with 0.040 Gage Including XB 75S-T (Bare and Alclad), R-301-T, Alclad 24S-T81, 24S-T (Bare and Alclad), 3S-1/2H, 14S-T, 52S-1/2H, and 61S-T*, W. F. Hess, R. A. Wyant and F. J.

Winsor, The Welding Journal Res. Suppl., August 1946.

24. *The Interpretations of Radiographs of Spot Welds in Alclad 24S-T and 75S-T Aluminum Alloys*, R. C. McMaster and F. C. Lindvall, The Welding Journal, August 1946.

25. *The Radiography of Spot Welds in Light Alloy and Ferrous Sheet Materials*, R. C. McMaster and F. C. Lindvall, The Welding Journal, September 1946.

26 *A Summary of the Spot Welding of High-Tensile Carbon and Low Alloy Steels*, W. D. Doty and W. J. Childs, The Welding Journal Res. Suppl., October 1946.

27. *Radiography of Spot Welds in Various Sheet Gages and Dissimilar Gage Combinations*, R. C. McMaster, F. C. Lindvall and L. P. Gaard, The Welding Journal, January 1947.

28. *The Classification and Recording of Spot-Weld Defects Revealed by Radiography*, R. C. McMaster, S. C. Lindvall and Edythe Dial, The Welding Journal, February 1947.

29. *Summary of Results of Tests Made by Aluminum Research Laboratories of Spot-Welded Joints and Structural Elements*, Tech. Note No. 869, National Advisory Committee for Aeronautics, E. C. Hartmann and G. W. Stickley, The Welding Journal Res. Suppl., April 1947.

30. *Handbook of Instruction for Aircraft Designers*, USAAF (AMC Manual 80-1), Rev. 1949.

31. *Recommended Practices for Resistance Welding*, American Welding Society, 1950.

CHAPTER 56

TRANSMISSION PIPE LINES*

INTRODUCTION

Extent of Application

WELDED STEEL pipe lines for transporting oil, gasoline and gas, literally criss-cross this country, many lines being over a thousand miles in length. Some lines are now being constructed, and others projected, which are over 1500 miles long. Many of these are in sizes undreamed of only a few years ago.

Welded steel pipe is used extensively for domestic water supply and distribution lines by municipalities, for transporting irrigation water and for penstocks for hydroelectric power development. These water pipe lines are not as long as the oil, gasoline and gas lines, but many of them are much heavier. For instance the Hoover Dam Penstocks are 30 ft. in diam. and have a wall thickness up to $2^3/_4$ inches.

This chapter covers the fabrication and field welding of transmission pipe lines of all sizes for gasoline, oil, gas, water and of pipe for penstocks. The first part of the chapter covers pipe lines for gasoline, oil and gas. The last part of the chapter covers pipe lines for water and penstocks for power development.

A. OIL, GASOLINE AND GAS PIPE LINES

General

Steel pipe suitable for welding is usually used for long transmission lines for either oil, gasoline or gas purchased under API or ASTM specifications. The only limitation usually is that the carbon content not exceed 0.35%. Seamless steel pipe is used extensively for all pressures and services. Commercially manufactured lap-welded pipe is used for relatively smaller sizes and pressures. Seam welded, flash-welded, electric-fusion welded, either manual or automatic, and automatic submerged arc fabricated pipe are also extensively used for all services and operating pressures. Until a few years ago the usual sizes employed and welded for transmission purposes was up to 16-in. O.D. for oil and gasoline transportation lines, and up to 26-in. O.D. for gas, the largest commercial sizes available in large quantities. In the last few years, oil lines 30 and 31-in. O.D. have been built and others proposed in sizes up to 36-in. outside diameter. Likewise for gas transmission over long distances, sizes of 30 and 31-in. O.D. have been built and many others are being planned up to 36-in. outside diameter. These large sizes have been fabricated in mass production by automatic submerged are welding.

The field welding and joining of these transportation lines is practically exclusively done by arc and gas welding; chiefly by manual arc welding. Oxy-acetylene welding is used to some extent in the field on short lines and smaller diameters of pipe. On large diameter pipe the present trend is to double lengthen the very large sizes at the pipe manufacturing or fabricating plant and ship the double lengths by freight or truck to the right of way. In other cases the pipe is assembled in double and even triple lengths by welding at predetermined unloading and distribution points and these longer sections trucked along the right-of way. This cuts the number of field welds at least in half. For this field welding, special aligning equipment and machine welding are employed. Submerged arc welding is commonly used.

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* Prepared by a committee consisting of G. H. Garrett, Thompson Pipe & Steel Co., *Chairman;* Walter H. Cates, Consolidated Western Steel Corp.; L. G. Christofferson, Chicago Bridge & Iron Company.; P. J. Bier, U.S. Dept. of Interior, Bureau of Reclamation; T. W. Greene, The Linde Air Products Co.; A. N. Kugler, Air Reduction Sales Co.; J. K. Richardson, U.S. Dept. of Interior, Bureau of Reclamation.

GOVERNING CODES AND SPECIFICATIONS

All steel pipe may be purchased under existing API or ASTM specifications. However, the quantities of materials involved are so enormous that as a rule, special arrangements are made and specifications drawn up between the pipe line company or user and the pipe manufacturer. The same is true in regard to codes or specifications covering the field erection and welding. The conditions vary so greatly in regard to terrain, size, length, operating conditions, etc., and the magnitude of the job is so enormous that as a rule special arrangements are made and specifications drawn up between the pipe line company and the contractor installing the lines. These may be general in nature or may cover a host of details down to the specific provisions for qualification and check of all welding operations even to the interpretations of gamma-ray inspection which in recent years has begun to be applied in the field to the largest of the pipe lines.

About the only important nationally known code or specification that is generally followed in this field is the ASA *Code for Pressure Piping*. This Code has two sections applying to transportation lines, one on Oil Piping Systems and another on Gas and Air Piping Systems. The latter section specifically covers high-pressure, cross-country transportation systems. It is one of the most liberal yet sound codes written and has given impetus to economical fabrication of extremely long gas transmission systems.

Up to 1927, with lap-welded pipe and even with seamless, a maximum design working stress of about 12,000 psi. was considered good engineering practice. With the use of field welding, the advent of high quality electric-welded pipe and high strength materials for both welded and seamless pipe, very much higher design working stresses have become common practice. Large diameter, high quality electric-welded pipe is now available having the following properties:

	Avg.	Min.
Transverse yield point, psi.	61,000	52,000
Transverse ultimate tensile strength, psi.	86,000	72,000
Joint efficiency, %	...	100

As a result of volume production of large diameter steel pipe having the above strength and based on experience gained in the use of pipe fabricated from plates by electric welding, the *Code for Pressure Piping* now permits a working stress in rural territory equal to 72% of the specified or demonstrated yield strength. Stresses as high as 39,500 psi. have been employed under this Code, corresponding to a minimum specified yield strength of 55,000 psi. Thus the working stresses customarily used in pipe-line design have trebled in the past 20 years and it has extended the economical feasible range of gas transmission from about 200 miles to over 1300 miles now employed.

MATERIALS

Materials for Oil and Gasoline Pipe

Pipe for oil and gasoline is generally of standard size and standard steel pipe analyses are commonly employed. Such pipes are covered by ASTM Specifications A53 *Welded and Seamless Steel Pipe* and A106 *Seamless Carbon-Steel Pipe for High Temperature Service*. For some service conditions, it may be necessary and desirable to use high-strength piping, in which case the increased strength is achieved through increasing the carbon or alloy content of the steel. Such pipe analyses may create difficulties in welding if the carbon content exceeds 0.35% or if the extent of alloys present produces a hardenable steel. In general, hardenable steels will require the use of pre- and postheating and special filler metal.

Recently there have been experimental applications of aluminum pipe for particularly corrosive conditions. Of the many analyses of wrought aluminum available, only those usually designated as *2S*, *3S*, *52S* and *61S* are considered as being suitable for welded pipe lines. Welding of these materials is generally accomplished by inert-gas metal-arc welding. (See Chapter 32 for further information on welding aluminum.)

Filler metal for shielded metal-arc welding low-carbon steel pipe lines should conform to *Specifications for Mild Steel Arc-Welding Electrodes* (ASTM Designation A233; AWS Designation A5.1). Any of the E60XX classifications of electrodes are satisfactory although there is a strong preference for the E6010 classification. High-strength piping requires weld metal

of equivalent strength; electrodes for these materials are covered by *Specifications for Low-Alloy Steel Arc-Welding Electrodes* (ASTM Designation A316; AWS Designation A5.5). The E7010, E7011, E8010 and E8011 classifications of electrodes have been used; however, for those steels which exhibit hardenability, the E6015 or E6016 classifications (or higher strength classifications of these types) may be used. Electrodes of these types, known as low-hydrogen electrodes, minimize the tendency to underbead cracking and reduce the necessity for, and amount of, preheating required.

For oxy-acetylene welding the welding rods should conform to the standard *Specifications for Iron and Steel Gas Welding Rods* (ASTM Designation A251; AWS Designation A5.2). Classification GA60 is recommended for all standard, low-carbon steel pipe; where higher strength welds are needed, rods of classification GA65 may be used.

The welding of aluminum piping by the inert-gas metal-arc process will require welding rods of the same types used in gas welding. However, no standard specification exists for this type of filler metal. For the welding of *2S* and *3S*, aluminum welding rods of the *2S* composition are recommended; for the *52S* and *61S* alloys, rods of the *43S* analysis are used.

When backing rings are used in welding piping it is important to insure that they are of weldable quality. The rings need not be of alloy composition even if alloy pipe is employed.

Materials for Gas Pipe

Gas transmission service normally requires use of the larger sizes of pipe in the standard range. However, the increased demand for natural gas has created a need for even larger pipe and this is being fabricated by welding. Since standard-weight pipe satisfies part of the demand, the same specifications apply in this field as for gasoline and oil pipe. For large-size pipe, it is important to consider any means for saving steel and the use of high-strength, light-wall pipe is quite common for the larger transmission pipe lines. The increase in strength is achieved by increasing the carbon content or through the addition of alloying elements.

The selection of filler metal for the welding of these pipes is on the same basis as for oil and gasoline lines. The mild steel analyses are welded with the E60XX electrodes, (Specifications A233) while the low-alloy steels are welded with the higher strength electrodes covered by Specifications A316. Again where steels which exhibit hardenability must be welded, it is suggested that the low-hydrogen types of electrodes (XX15 and XX16 classifications) be employed. Filler metal for gas welding will, of course, be governed by Specification A251 on the same basis as for oil and gasoline pipe.

Since the principal difference between oil and gasoline pipe and gas pipe is in the size and since the method of manufacturing the larger sizes needed for this work is unique, a description is provided here. These large diameters of gas pipes are fabricated by welding cyindrical sections formed from flat plate. Fundamentally, this is not a new technique; however, the special procedures employed establish this as a new pipe-line technique. Thirty-inch O.D. pipe is a typical size used for gas service and a description of its manufacture will provide an understanding of this new method.

The operations start with steel plates 30 ft. long, about 92 in. wide and of a thickness appropriate for the operating pressure. After flattening and trimming to size these plates are grit blasted along the edges. Following this, the edges are prepared for welding and the plates are rolled into cylindrical shape, 30 ft. long. The next step is the welding of the longitudinal seam by the submerged arc process. In performing this operation the cylinders are continuously fed, end to end, through a welding machine. The welds are backed up inside by water-cooled copper backing bars. After welding the pipe, which is somewhat less than 30 in. in diam., it is placed in dies and subjected to internal hydrostatic pressure which expands it to exactly 30 in. outside diameter. This operation serves to increase the yield strength of the pipe and at the same time insures uniform roundness and straightness; it also provides a hydrostatic test of the welded joint. Finally, after facing the ends, two 30-ft. sections are welded together by submerged arc welding to provide 60-ft. lengths which are shipped to the field. Pipe manufactured by this method has been used on the natural gas line from Texas to California.

DESIGN

It has been shown that the principal difference between oil and gasoline pipe and gas pipe is a matter of the range of sizes. In general, pipe for the transmission of gasoline and oil will be smaller in size than pipe employed to convey natural gas. Further, the range of pipe wall thicknesses is substantially the same for both classes of service. Therefore, in considering the design of joints for welded transmission pipe lines, it is logical to treat these two groups as one.

The physical dimensions of pipe lines are governed by the operating conditions; thus the required flow through the line will dictate the size of pipe needed. The thickness of the pipe wall is largely governed by operating pressure, but may be further influenced by corrosive conditions (both external and internal) and in some cases it may be necessary to use a protective coating or cathodic protection or increase the wall thickness beyond that dictated purely by strength considerations. Since virtually all transmission pipe lines are buried underground, it is not necessary to consider stresses which are essentially of a structural nature, which occur when a pipe line is carried above ground. Similarly, expansion and contraction do not present the problems encountered in overhead steam piping, for example. With the pipe buried at appreciable depths, generally below the frost line, and with the continuous passage of fluid through the pipe, it may be considered to be operating at essentially constant temperature. If temperature changes are involved, they are relatively small in magnitude and of such a protracted nature as not to cause any serious stresses. In addition, the methods of installing pipe in the trench, under compression, tend to reduce the opportunities for imposing direct tension stresses on the line. In fact the stresses induced by the usual operations incident to pipe-line construction will be of greater magnitude, and more likely to cause failure, than those encountered in service.

Since the fundamental design considerations are the same whether the pipe line is installed with mechanical or welded joints, it follows that the welding design problems are concerned principally with joint designs. As compared with other welding operations, welded pipe joints create another problem in that they are accessible from only the outside, since diameters are normally too small to permit welding from the inside. Reference to Chapter 39 will disclose that joints welded in this manner are difficult to make with complete penetration and secure optimum strengths.

Through the years many attempts have been made to develop joint designs which would provide the assurance of strength and soundness. Among the early designs were adaptations of the bell and spigot joint long familiar in cast-iron pipe practice. However, the weld used in this joint is a fillet weld and the joint strength is inferior to that obtained with a butt weld. Another early type was the double bell joint with an internal liner or backing ring. This backing ring was of the same dimensions as the pipe and the ends of the pipe were belled sufficiently to accept this ring. This joint type has not survived because it is costly to prepare the pipe ends and provide the ring, and because of the difficulty of inserting off-standard lengths in a line in the field, since no means are available for providing the belled ends in the field.

Thus it will be seen that the single-Vee groove butt joint, without or with a backing ring, has proved to be the most satisfactory and economical joint design for welded pipe lines. The beveling of the pipe ends is readily performed in the pipe mill, shop or in the field. In the mill or shop a pipe lathe is commonly used whereas in the field a machine oxygen-cutting torch (commonly called a pipe-beveling machine) is more practical. Manual oxygen cutting, while frequently employed, does not yield as clean nor as accurate a cut as machine cutting. The standard mill bevel angle currently available is $37^1/_2$ deg.; this is a compromise between the older bevel angle of 45 deg. and the newer angle of 30 degrees. Generally, a root face of $^1/_{16}$ in. is provided. This joint preparation is acceptable for pipe thicknesses up to $^3/_4$ inch. The single-U groove butt joint should be used for heavier pipe. (See Chapter 39.)

The use of backing rings is largely controlled by the service requirements and by maintenance procedures. If it is essential that complete fusion to the root of the joint be assured, without protrusions (icicles) within the pipe bore, then the use of backing rings is indicated. However, if *go-devil,* internal pipe cleaning devices are to be employed, as in oil lines,

then backing rings cannot be tolerated. These rings constitute an obstruction in the pipe and, therefore, reduce the cross-sectional area. They also add to the cost of making the joint. The current pipeline practice of depositing (with a competent welder) a root bead using $^1/_8$-in. diam. electrodes of classification E6010 will produce thoroughly reliable joints through which cleaning devices may pass freely.

The design of backing rings, if used, is of the utmost importance. Recent test work indicates that a ring having a flat surface or provided with a shallow groove is most satisfactory. Formerly, rings equipped with either continuous ridges or intermittent, short segmental ridges, were considered desirable. It was assumed that such ridges provided a means for spacing the root of the joint thus assuring root penetration. Since these rings were used almost exclusively with shielded metal-arc welding, it was further assumed that the arc would completely melt them and incorporate them in the weld. However, it has been demonstrated (on welder qualification tests employing the root-bend test) that the ridge induces small cracks in the zones between the ridge and the root faces. This condition can be avoided by using either flat or shallow-grooved backing rings.

The design of joints for inert-gas metal-arc welding of aluminum piping follows established practices. Thus, for thicknesses up to about $^5/_{32}$ in. the square-groove butt joint generally is used. For thicknesses $^3/_{16}$ in. and greater, the single-vee groove butt joint is employed.

WORKMANSHIP

Construction Practices

In the construction of welded pipe lines certain collateral operations are commonly involved whether arc or gas welding is used. The quality of the finished line and the speed with which it is installed are directly influenced by these operations, hence proper control and coordination of them is of vital importance to the successful completion of a welded pipe line.

The preliminary preparations for pipeline construction follow the general pattern for all engineering work. Thus, surveys of the proposed units of the line are made. These surveys may be made by the conventional transit line method or the newer aerial techniques. Following this, the necessary plans are prepared together with specifications. These specifications will encompass all phases of the work, equipment and materials and testing, and must cover all the detail requirements for welding, including welder qualifications. The type of steel pipe to be employed is usually very carefully specified to insure steel of weldable quality and even sometimes the amount of preheating, if any is deemed advisable, that may be desirable before welding.

With the units of the line established by the surveys and the right of way secured, the next step is that of clearing the right of way of trees and obstructions, special grading of hill or mountain passes, etc., so that construction operations may be carried forward. Following this the ditch for the pipe is dug for which it is almost universal practice now to employ ditching machines. The next operation, that of stringing the pipe along the right of way may occur at this stage or may precede the ditching operations. Trucks or tractors are employed for moving the pipe from the railroad cars to conveniently located distributing points along the line. At these points two pipe lengths may be welded together before distribution along the right of way. Tractors equipped with booms generally distribute the individual or double lengths of pipe along the ditch. It should be noted that all of these operations are preliminary to actual welding.

Firing-Line Method.—In former years of pipe-line welding, a large organization, spread over several miles, was required because of the general practice of welding two to five or more lengths together in what was known as the *firing-line method* of construction. For installing pipe by this procedure, the following organization was generally employed:

(*a*) Line-up gang.
(*b*) Firing-line gang.
(*c*) Tie-in gang.
(*d*) Lowering gang.
(*e*) Bell-hole gang.
(*f*) Back-filling gang.

The function of the line-up gang was to line up the pipe on skids or dollies adjacent to or over the trench. Clamps were used to hold the pipe ends in alignment while tackers in the gang made the required number of tack welds. In these lining-up operations it was common practice to tack weld from two to five lengths

of pipe into a so-called *string* in preparation for the firing-line gang. The exact number of lengths in a string was largely dictated by the terrain, length of line, job conditions and the availability of equipment.

The firing-line gang deposited the actual welds on these strings of pipe employing one of two generally accepted procedures: (1) Operators could be stationed at each weld in a string, each making a complete weld in the string while a helper turned the pipe on dollies or skids; or (2) one operator could make all the welds in a string while a helper turned the pipe. Since the pipe was rotated during welding, welding could be done in the flat position only and welders skilled in welding overhead or in a fixed position were not necessary.

These series of strings of welded pipe ranging from 80 to 200 ft. (40-ft. lengths assumed) were then joined together by the tie-in gangs making fixed-position welds. Lowering gangs, bell-hole gangs and back-filling crews then completed the laying of the line.

Composite-Construction Method. — A construction method that helped to dictate the above-described procedure of laying cross-country lines was the use of the so-called *composite-construction method.* Composite construction, as the name indicates, is a combination of welded construction with some form of mechanical coupled joints. It has been used in some instances for large-diameter gas lines where the difficulty in securing allowances for proper expansion and contraction in a solid welded line made the mechanical connections desirable. Further, the use of couplings, usually of the friction or pressure type, eliminated all fixed-position welds. Fabricating practices were used which are similar to those used in the firing-line method. Strings of three to five lengths were roll welded along the right of way by the firing-line gang. Following this the strings were placed on skids over the trench and the couplings applied to the ends. Then a bolting gang made up the couplings. The line was then given a protective coating and lowered and backfilled.

Stove-Pipe Method.—The procedure today that is in general practice is to lay the line, length by length, with all the various crews closely coordinated and grouped together over a relatively short distance along the right of way. This requires that each pipe be welded into the line by a fixed-position weld. While this method requires more skill of the welders practically all of them today are highly skilled in making overhead or fixed-position welds. This method of construction is known as the *stove-pipe method* of laying cross-country lines and involves the following steps.

The right of way is cleared, pipe strung and the ditch dug ahead of the welding operations. Each joint is lined up on skids across the ditch, and as a subsequent length is laid over the skids two welders immediately tack weld it and apply the first bead completely around the pipe. The welders work on opposite sides of the pipe. Following the welders making this root bead comes the main welding gang. These welders complete each weld by adding a sufficient number of additional beads, usually two or three depending upon the pipe wall thickness, by the usual tie-in position welding method.

Bending of the pipe is done either on single lengths before they are placed over the ditch and tacked, or after the first bead is welded.

Figures 1 to 5 illustrate this sequence of operations. Figure 1 shows a line-up crew lifting a pipe section onto a skid with the aid of a tractor. Figure 2 shows the pipe sections being lined up and tacked. Figure 3 shows the use of a line-up clamp for lining up plain end pipe without a backing. Figure 4 shows two welders making a root bead and Fig. 5 shows a welder completing the joint.

River Crossings and Special Constructions

The finished pipe line, buried in the ground, must be connected to pump or compressor stations located at convenient intervals. The installation of the large amount of piping at these stations is handled by special crews as the work is of a special nature. Pipe-line crossings under roads and railroads involve special construction, and are generally built by crews especially equipped for this work.

River crossings are always solid welded throughout. The pipe is usually roll welded in long sections of 200 ft. or more. If the river is comparatively narrow, the long sections are welded together on the banks and the entire line pulled across the

Fig. 1.—Lifting Pipe onto Skids

Fig. 2.—Pipe Being Lined Up and Tacked

Fig. 3.—Use of Line-Up Clamp

river in one section, after which it is tied into the main line on the banks. On very wide rivers, the pipe line is lowered from a barge as shown in Fig. 6. The pipe is usually welded into 80-ft. sections before it is placed on the barge. It is

Fig. 4.—Two Welders Making Root Bead

then lowered into the river, one section at a time, the section on the barge being welded to the section that is practically in the water. Extra heavy pipe, often 1/2-in. thick or more, is used. For added protection, heavy split sleeves, as shown in Fig. 7, are sometimes welded over the pipe joints. The weight of these sleeves also helps in keeping the pipe down on the river bottom. Cast-iron clamps are sometimes used to weight the pipe. For larger diameter gas pipe, which will readily float, the main line is broken down into several smaller lines, by means of bank headers. Another type of construction extensively used for large gas lines is to cross the rivers on a cable-suspension type bridge. Unsupported spans between towers range up to 2000 feet. Suspension type bridges also are used across deep canyons and dry washes.

The following innovations that are being used on large-diameter gas lines are worthy of special notice:

1. The development and application of new types of mechanical internal travel, internal line-up clamps, which materially help in aligning and in welding, particularly the welding of the root bead. These internal line-up clamps are very effective in facilitating double-lengthening operations.

2. Small angle bends made by cold-bending methods using specially designed, powerful apparatus, as shown in Fig. 8. More acute bends are formed by slicing factory bends on the right of way immediately before installation.

3. Pipe is double lengthened in the field by automatic welding such as submerged arc welding. Such an operation is shown in Fig. 9.

4. Spot gamma-ray inspection is used quite widely and promises to be used even more in future pipe-line construction.

Fig. 5.—Making Tie-In Weld

INSPECTION AND TESTING

General

Inspection, as a general phase of pipe-line construction, includes many operations, some of which are not peculiar to the welding operations. In addition, the

difference between oil and gasoline piping and gas piping is essentially one of size, hence a general discussion will apply to all types. An extensive discussion of the details involved in the inspection of weldments, including typical weld defects will be found in Chapter 42.

Qualification of Welders and Procedures

It is necessary to test all welders before their employment on actual welding operations. This qualification of welders is a standard procedure on all important welded construction work in order to assure maintenance of weld quality and should be made employing the procedure to be used in the construction line. The ASA *Code for Pressure Piping* provides for qualification of the welding procedures and welders, following the pattern established in the AWS *Standard Qualification Procedure*, given in Chapter 60. Qualification tests for pipe welding are different from those used in plate work because the position of the pipe rather than the position of the weld controls. The standard test positions for pipe are (1) horizontal pipe position, rolled; (2) horizontal pipe position, fixed; and (3) vertical pipe position, fixed. Welding in the horizontal pipe, fixed position requires (in order, starting at the top) flat-position welding, vertical-position welding and overhead welding; if the direction is from the bottom upward, then this sequence is reversed.

On pipe-line construction where the work can be segregated, it is sometimes possible to arrange the work so that a given crew will have to weld in only one position, e.g., horizontal pipe position, rolled, in which case qualification need be only for that position. If, however, a welder will work in all positions, then he must qualify in all positions.

In qualifying under the ASA *Code for Pressure Piping*, procedure qualification involves a number of involved, expensive tests. However, once it has been successfully completed it is not necessary to requalify it unless a major change is made in the techniques employed. Welder qualification under an approved procedure is relatively simple, involving the making of sample pipe welds in the positions to be encountered on the job. From these sample pipe welds, guided-bend test specimens are removed and subjected to the guided face- and root-bend tests. Acceptable specimens are required to bend to the capacity of the guided-bend-test jig without showing any cracks or other open defects greater than $^1/_8$ inch. Portable equipment is available or may be fabricated for conducting these bend tests in the field, thus expediting the completion of welder qualification on the job.

In the construction of transmission pipe lines for petroleum products, it has long

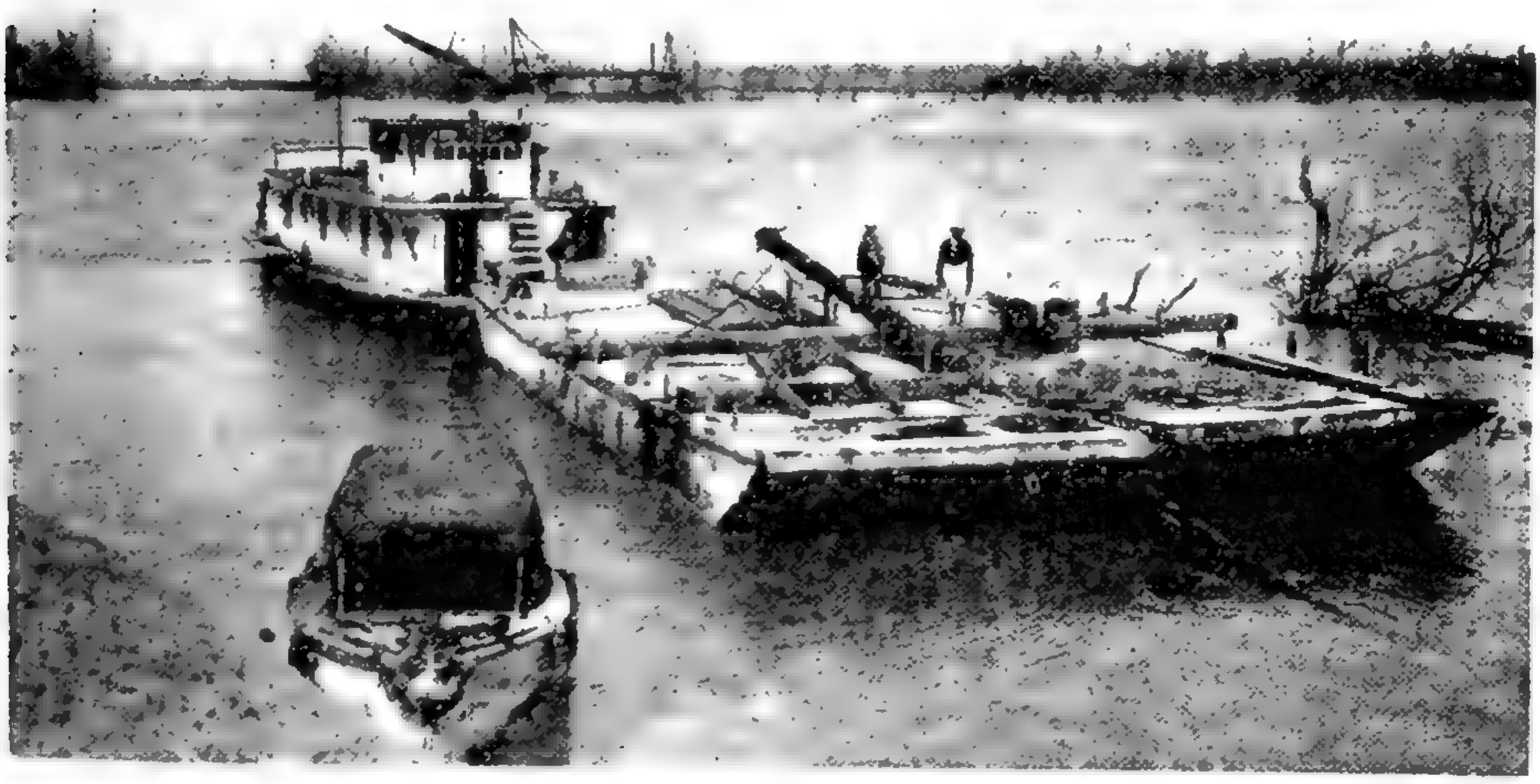


Fig. 6.—Laying River-Crossing Pipe

been the practice to conduct welder qualification tests in the field. The need for this practice is apparent when it is realized that operations are scattered over wide areas on a large pipe line.

Fig. 7.—Reinforcing Sleeves for River-Crossing Pipe

Welders are required to make sample pipe welds in the position and under conditions to be encountered on the pipe line, from which coupons, containing the weld in the middle, are removed by manual oxygen cutting. These coupons are subjected to a tension test using a portable tension-testing machine. Formerly, it was merely required that these coupons break outside the weld; more recently, attempts have been made to prepare more accurate specimens and conduct standard tension tests, recording the tensile strength. While this method of welder qualification testing is still employed, it is not as searching as the guided-bend test and has been largely superseded on important pipe lines by the tests prescribed in the ASA *Code for Pressure Piping*.

Inspection During Welding

During the progress of a pipe line the welding inspector should check to make certain that the requirements of the procedure specification are being observed. Careful inspection at this phase of operations can avoid costly errors. The inspector should ascertain that the pipe is of the proper analysis, size and weight and that the correct classification of filler metal is being employed. He should also check that all welders have been qualified for the welding they are performing.

Inspection After Welding

Inspection of a welded pipe line is difficult because there is no completely satisfactory non-destructive test method that is applicable to transmission pipe lines. Inspection by means of X-rays and gamma rays, while possible, usually is too costly and cumbersome to be of any value except for spot checking in special cases. Magnetic particle inspection techniques are subject to the same limitations. Because of these considerations inspection of welded pipe lines is limited to visual examination, spot checking employing destructive tests, pressure testing and service testing.

Visual examination of completed welds by experienced inspectors can reveal much information about the quality of a weld. However, it cannot disclose defects at the root of a joint, nor can it provide an accurate measure of the soundness of a weld. It is, however, the first step to be

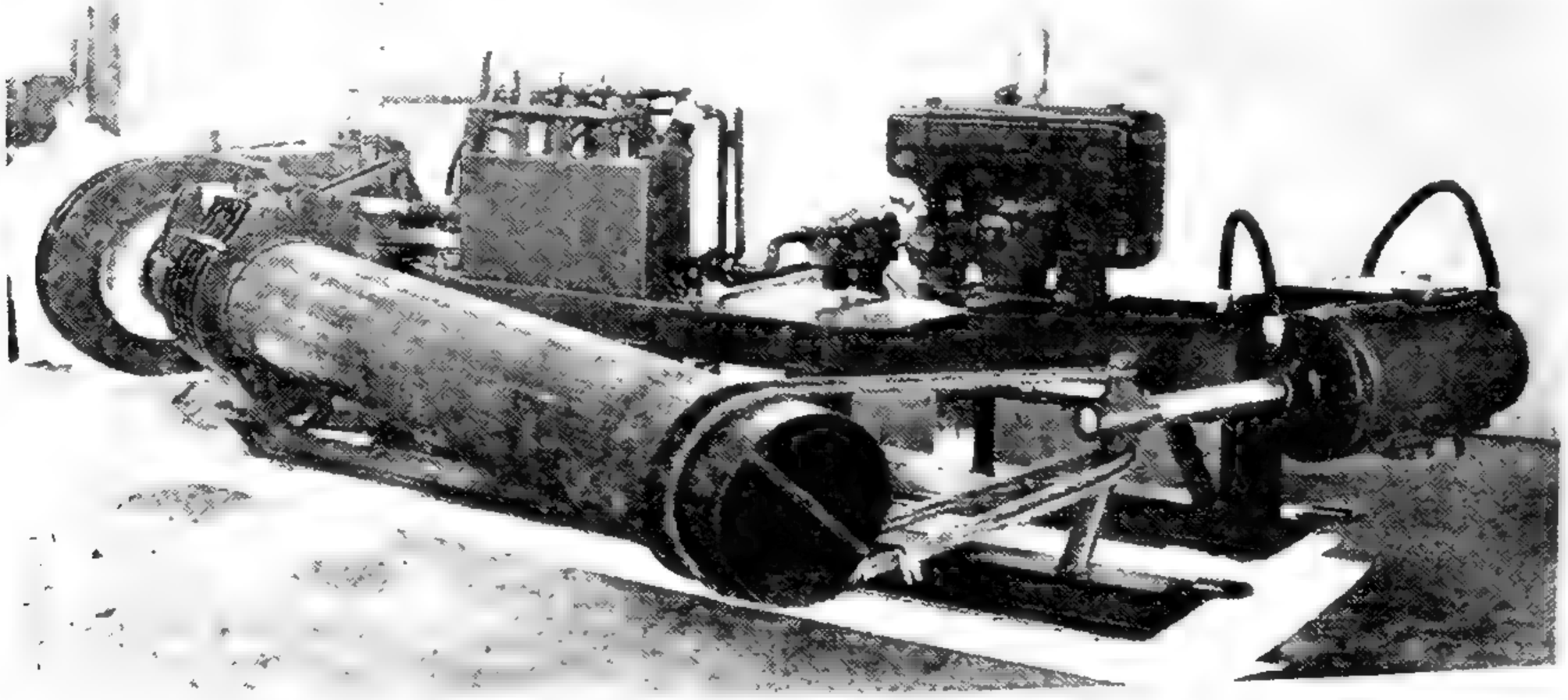


Fig. 8.—Cold-Wrinkle Bending Large Diameter Gas Pipe

taken before any of the other tests are applied. It should always precede spot checking by destructive methods.

Spot checking provides for the testing of a stipulated number or percentage of the joints produced on a line, and samples from all welders should be included in the batch selected. The joints thus selected for testing are completely removed from the line and the line repaired by drawing the free ends together (if possible) and rewelding, or welding in a short section of pipe (two welds required) to replace the piece removed. The welds

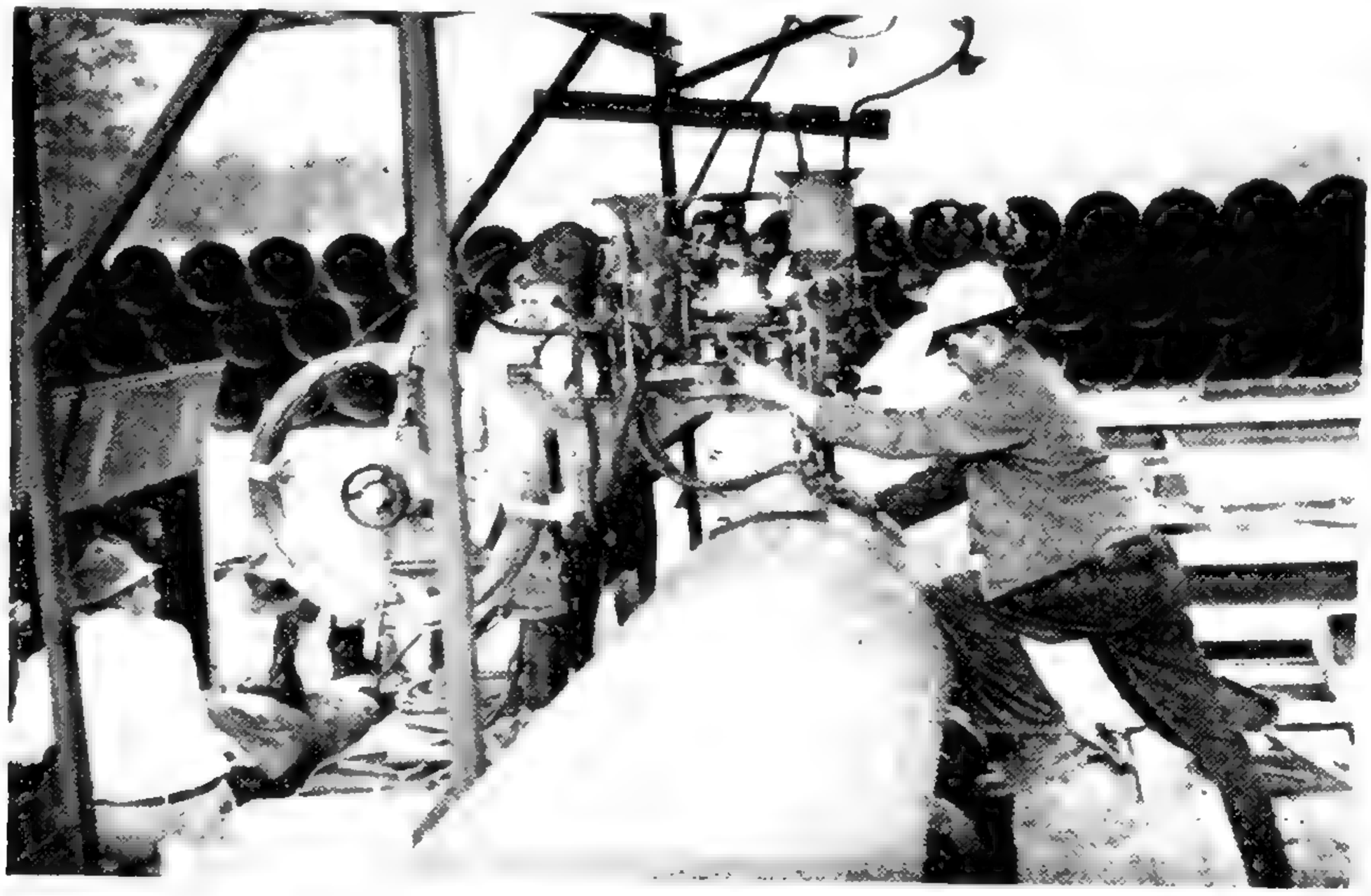


Fig. 9.—Double Lengthening Large Diameter Gas Pipe

that have been removed from the line are subjected to a series of tests which may be the same as those used for operator qualification or a group of separate tests mutually agreed upon by owner and contractor. Failures in these tests require careful evaluation to detect the source of poor quality welds. Generally, when such welds prove to be satisfactory, the cost of rewelding is borne by the owner; the cost for welds which fail is charged to the contractor. This same procedure is employed on welds which the inspector rejects, after visual examination, necessitating their removal from the line.

Pressure testing of a completed pipe line with compressed air is a large job and extremely expensive and, therefore, almost never undertaken. Similarly, hydrostatic testing is impractical on completed lines. However, short sections of a line may be tested with compressed air (usually 50 to 100 psi.) prior to tying them into the finished line. The length of such sections may vary from a few hundred feet up to a mile or more. The usual requirement is that the line hold the test pressure for a stipulated period of time, making appropriate corrections for temperature changes. During the period of air testing each weld is checked by applying soapy water and observing for leaks. Minor leaks disclosed by such tests may be repaired by rewelding the affected area, but a joint which leaks all over should be completely removed and rewelded.

Pressure testing, because of economical limitations, cannot be applied generally to transmission pipe lines. Therefore, the usual practice is to test the completed pipe line by subjecting it to actual working conditions, i.e., carrying oil, gasoline or natural gas at the required pressure. Of course, this technique carries with it the problem of handling failures should they occur. Fortunately, however, the petroleum industry has developed a number of procedures for repairing and even installing new sections in welded pipe

lines operating under pressure. Obviously, such methods should be used in the event of failures during service testing.

B. WATER PIPE LINES

General

Welded steel pipe is used extensively for water pipe lines for conveying water for domestic, industrial and irrigation purposes. Municipalities use it for their larger supply lines to reservoirs, and in distribution systems within their incorporated limits. It is usually made of low-carbon steel, and can be purchased under a number of specifications.

For flow lines to small municipalities, for distribution systems in municipalities and for industrial purposes, pipe sizes range from 6 in. to a few feet in diameter. For large supply lines there is no limit to the diameter in which the pipe may be fabricated.

GOVERNING CODES AND SPECIFICATIONS

Welded steel water pipe is manufactured in either a pipe mill or a pipe fabricating plant. The processes used for welding are: lap welding, resistance seam welding, flash welding, electric fusion welding and automatic submerged arc welding. In addition to pipe welded by the above processes, seamless steel pipe is also used.

Pipe for conveying water is usually purchased to conform to: AWWA *Standard Specifications for Electric Fusion Welded Steel Water Pipe of Sizes Up to But Not Including 30 Inches* (Serial Designation 7A.4) and AWWA *Standard Specification for Electric Fusion Welded Steel Water Pipe of Sizes 30 Inches and Over* (Serial Designation 7A.3). Pipe purchased under ASTM Specifications *Electric Fusion Welded Steel Pipe (Sizes 30 In. and Over)* (Serial Designation A134) or *Electric Fusion Welded Steel Pipe (Sizes 4 in. to But Not Including 30 In.)* is satisfactory for water service, as is pipe conforming to API *Specification 5L for Line Pipe.*

For especially large diameter pipe, having wall thicknesses greater than 1¼ in., or for water pipe placed above the ground and supported by stiffener rings, it is advisable to use the specifications and design practice as discussed in the section of this chapter on penstocks.

Water pipes usually have some kind of coating inside and outside to protect them against corrosion. For mildly corrosive conditions, a good quality of coal-tar paint is used. For severe corrosive conditions, either inside or outside, the pipe is usually protected with a coal-tar enamel lining or coating applied in accordance with AWWA *Standard Specifications for Coal-Tar Enamel Protective Coatings for Steel Water Pipe* (Serial Designation 7A.6 for pipe of size 4½ in. up to but not including 30 in., and Serial Designation 7A.5 for pipe of size 30 in. and over).

MATERIALS

Pipe for water supply service is usually made of low-carbon steel. Water pipe lines (except penstocks) normally operate under much lower pressures than do pipe lines for gas, gasoline or oil, so that it is not necessary to use steel having as high a tensile strength for water pipe lines as for pipe lines for the oil industry.

DESIGN

In designing a steel water pipe line it is necessary to have a profile made from a survey of the line. From the information contained on the profile and other information, such as quantity of water to be carried, surge conditions, nature of the soil from a corrosion standpoint and any unusual operating conditions that may exist, it is possible to determine the diameter and wall thickness of the pipe, location and size of air valves and blow-off valves, and type of protective coating to be used on the inside and outside of the pipe.

After determining the diameter of the pipe line by the usual design formulas, the next procedure is to calculate the internal working pressure by adding to the pressure shown on the profile, such additional pressure as might be caused by water hammer.

Proper allowance should be made for expansion and contraction of the pipe line, particularly during the construction period, if the field joints are to be welded. If sleeve-type compression couplings are used for the field joints, it will not be necessary to give any further consideration to the matter of contraction and expansion.

Slight bends may be made in field joints of water pipe lines to fit the profile of the

ground, provided lap-welded, slip bell joints (bell and spigot) are used in the field, or sleeve-type, compression couplings are used. Figure 10 is an illustration of a long radius bend made in the field. The pipe in this case was 27 in. in diam., and the lengths were 40 feet. Slip bell, lap-welded field joints were used. For making bends in large-diameter pipe or for making bends of several degrees in small pipe, special elbow sections of the correct degree are usually fabricated at the pipe mill or in the pipe fabrication plant.

Fig. 10.—Curve in 27-In. Diam. Pipe

Several types of field joints which may be used in a pipe-line design are described in the AWWA Specifications 7A.3 and 7A.4 previously referred to. The type of joint to be used is usually determined by field conditions and by the thickness of the pipe wall. The slip bell type of joint is very satisfactory for pipe of wall thicknesses up to $^{5}/_{8}$ inch. For pipe diameters 30 in. and larger, slip bell joints are usually fillet welded inside and outside. If the interior of pipe under 24-in. diam. is lined with coal tar, an enameling crew cannot get inside of the pipe to re-enamel after welding, and the sleeve-type, compression coupling, or bell and spigot joint for caulking, is usually used for making the field joints.

WORKMANSHIP

Construction Practices

If the pipe line is to be buried, it is assumed that the general procedure will be carried out as with any other pipe-line construction—the right of way is to be cleared away, access roads provided and a suitable trench provided in which to lay the pipe. The pipe is distributed along the right of way and any specials are distributed at their proper laying positions. If the pipe is enamel lined or coated, considerable care must be employed so that in the hauling and distributing operations, neither the inside lining nor the outside coating is damaged. Trucks for hauling this type of pipe are usually provided with padded bunks cut out to fit part of the circumference of the pipe. When coated pipe is distributed along the right of way in rocky ground, the ends of the pipe should be placed on wood blocks so that none of the coating on the outside of the pipe rests on rocks or gravel.

Whether field-welded joints or sleeve-type, compression couplings are used, the pipe is usually picked up, one length at a time, and joined together in the bottom of the trench. Bell holes are provided for welding and coating field joints, or for tightening the bolts in the sleeve-type, compression couplings. After the field joints are tacked, or after the couplings are bolted, it is advisable to cover the pipe lengths between field joints before the joint is finished and tested, in order to minimize expansion and contraction.

Pipe lines crossing rivers require special consideration as to their location. If the elevation permits, such pipe lines are frequently carried across the stream on piers as shown in Fig. 11.

The procedure for welding field joints on steel water pipe lines is covered by the AWS-AWWA *Standard Specifications for Field Welding of Steel Water Pipe Joints;* general information on the subject will be found in some of the sources listed in the bibliography at the end of this chapter.

Welding in the field at very low temperatures is not generally advisable However, it can be done successfully, provided a proper welding procedure is followed, and provided also that the pipe is

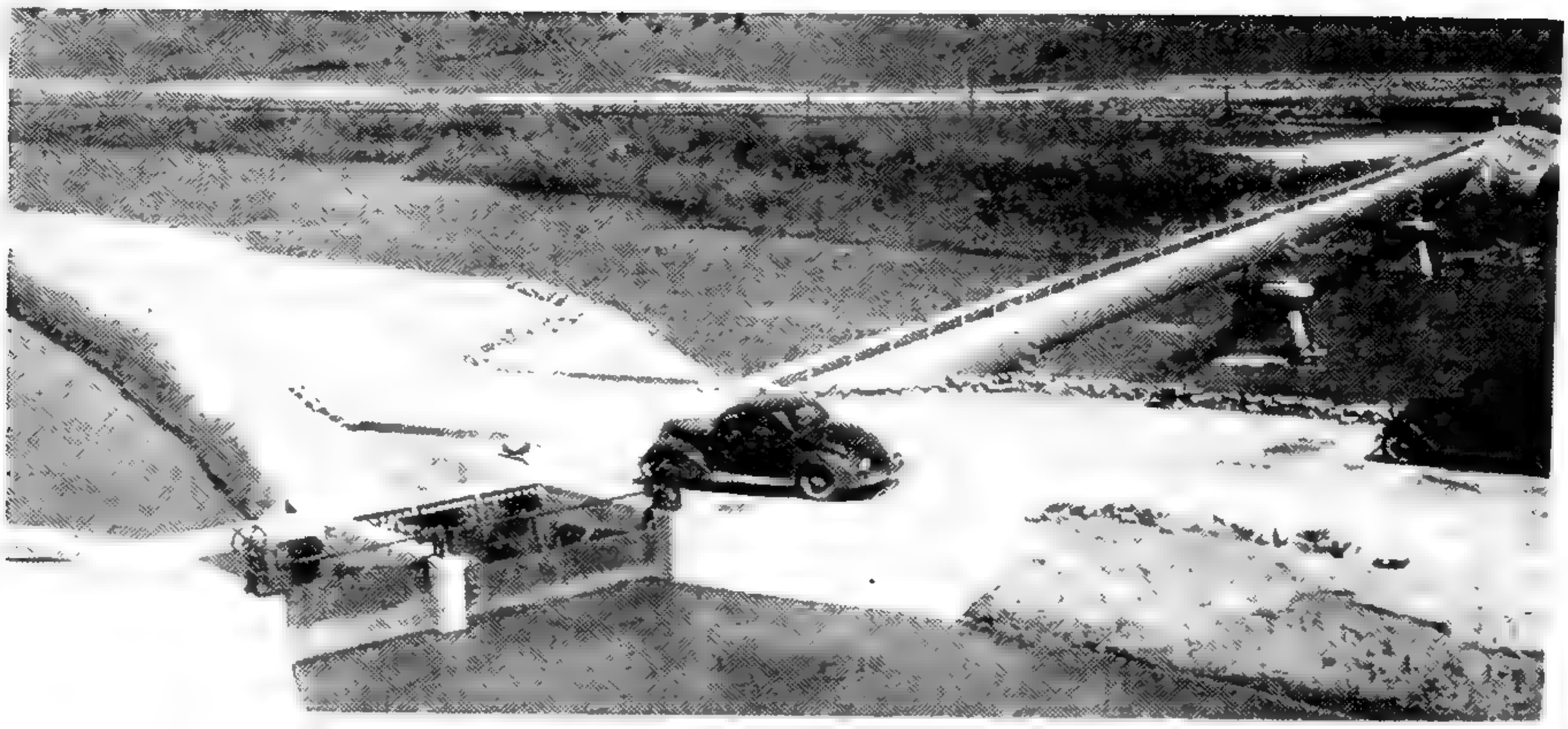


Fig. 11.—Carrying Pipe Line Across River

One-hundred thirty-four-foot spans.

made of a grade of steel which will permit welding at low temperatures. Figure 12 shows a welder welding a field joint when the temperature was 35° below 0°F.*

A section of the Bouquet Canyon water pipe line for the City of Los Angeles is shown in Fig. 13. The diameter of this line ranges from 94 to 80 in. and the thickness from $^{3}/_{8}$ to $1^{1}/_{16}$ inches.

* See bibliography.

Fig. 12.—Field Welding Pipe at −35°F.

FIELD INSPECTION AND TESTING

Inspection and qualification requirements for water pipe lines are prescribed in the AWS-AWWA *Specifications for Field Welding of Steel Water Pipe Joints.* Recommendations given under Inspection in Part A—Oil Gasoline and Gas Pipe Lines, of this chapter are applicable to the field welding of water pipe lines.

C. PENSTOCKS AND LARGE DIAMETER WATER PIPES

General

Penstocks are used for the conveyance of water under pressure to hydraulic turbines for the generation of electric power. Their construction requires a high degree of safety and smooth, streamlined interior surface is necessary to reduce hydraulic losses and to conserve the available pressure head. The strength and flexibility of steel make it especially suitable for the variety of pressure fluctuations met in turbine operation so that steel penstocks are generally used. Large diameter penstocks are usually made from steel plates rolled into cylindrical sections with the ends of adjacent sections welded together. This welding is done in the shop for sections whose diameters are within shipping limits and in the field for larger diameters.

The same principles of design and construction which govern penstocks apply equally well to very large high-pressure water pipe lines.

GOVERNING CODES AND SPECIFICATIONS

At present there are no nationally recognized specifications for the design and fabrication of penstocks. Because of this it is usual practice to prepare detailed specifications for each job. Design requirements for such specifications may be based on the accepted standards for the design of pressure vessels as in the ASME *Code for Unfired Pressure Vessels* and the API-ASME *Code for Unfired Pressure Vessels for Petroleum Liquids and Gases.* Fabrication requirements should cover in detail the type of steel to be used, specific workmanship requirements and the inspection and testing to be employed.

Welding procedures should be required to be qualified before being used, and all welders should be qualified before being permitted to weld penstocks. Specification requirements should also include any specified detailed instructions necessary regarding assembling and laying of pipe sections as well as painting requirements. As actual soil conditions at the site of installation and the adaptability of materials and equipment during construction may materially affect the economy of the installation, contract specifications should contain provisions to adapt the construction to such conditions as are peculiar to the particular job.

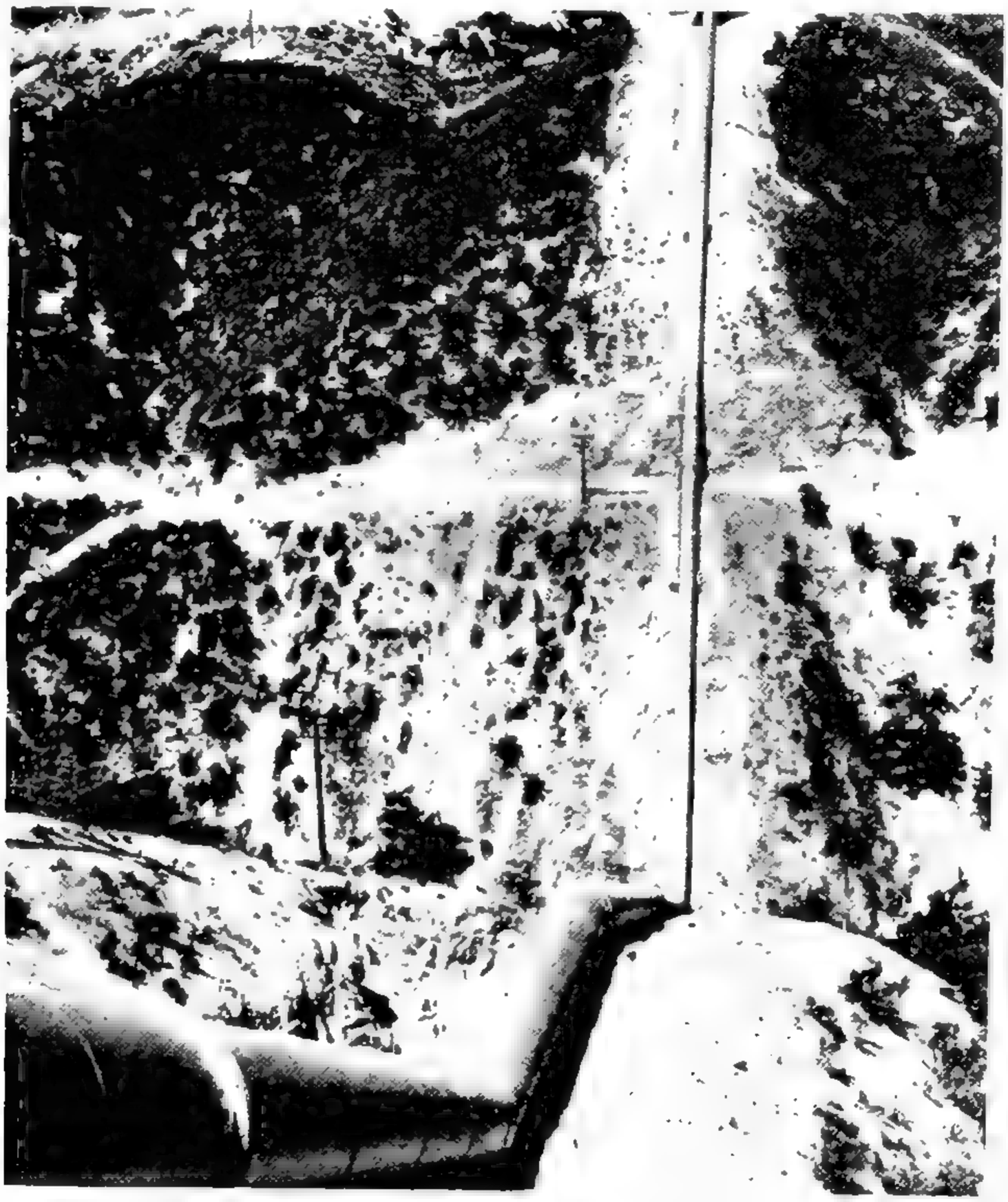


Fig. 13.—Typical Section of Overland Water Pipe Line

MATERIALS

Welding processes and procedures have been developed to the extent that it is now possible to weld a very large variety of steels in most of the thicknesses usable in penstock fabrication, including those which are to operate under high internal working pressures and are to be of very large diameters. A high quality of steel, such

as firebox and flange quality suggested here for use in penstocks, is not required in the construction of water pipe lines because they are not subjected to the surges which occur in penstocks.

In choosing materials for penstocks it should be remembered that the quality of the completed job will be influenced by a set of conditions, such as the type of steel and electrodes used, the welding procedure, the welding current, welding speed, joint design, the skill of the welders and weather conditions. The combination of these variables will determine the quality of the finished product.

Carbon-steel plates of firebox quality provide the most satisfactory material for welded penstocks. These steels have good welding qualities and insure welds of the desired ductility to withstand the heavy surges and waterhammer shocks occurring in turbine operation. The above steels are produced in accordance with ASTM *Standard Specifications for Low and Intermediate Tensile Strength Carbon-Steel Plates of Flange and Firebox Qualities* (Serial Designation A285) which is rolled in Grades A, B and C for plates 2 in. and under in thickness.

The chemical compositions and mechanical properties of the above steels of firebox quality are given in Table 1.

For plates over 2 in. in thickness another type of firebox quality steel is used which is produced in accordance with *Standard Specifications for Carbon-Silicon Steel Plates of Ordinary Tensile Ranges for Fusion-Welded Boilers and Other Pressure Vessels* (ASTM Serial Designation: A201). This type of steel is rolled in Grades A and B, having the chemical compositions and mechanical properties given in Table 2.

For less important penstocks, or when the above steels are not available, steel conforming to ASTM *Specifications for Low and Intermediate Tensile Strength Carbon-Silicon Steel Plates of Structural Quality* (Serial Designation A283) may be used. This type of steel is rolled in Grades A, B, C and D, of which Grades B and C are considered to be the most suitable for penstocks. The minimum tensile strength of Grade B varies from 50,000 to 60,000 psi., and Grade C from 55,000 to 65,000 psi. The minimum yield point for Grade B is 27,000 psi., and for Grade C it is 30,000 psi., and the minimum elongation for both is 1,500,000/tensile strength. Although the maximum carbon content is not specified, it is not expected to exceed 0.30% except for very heavy plates. The phosphorus and sulfur contents of these steels are not to exceed 0.06 and 0.05% respectively.

The API-ASME Code restricts the use of A7* and A283 steels to thicknesses not exceeding $^3/_4$ inch. It also requires that vessels made from carbon steel in excess of $1^1/_4$ in. thickness, and for thinner plates exceeding a thickness of $(D_1+50)\div 120$ (where D_1 is the inside diam. in inches but not less than 20) must be stress relieved. For high quality welds, applied either manually or automatically, semi-killed steel is recommended. This class of steel is partially deoxidized and has less porosity and segregations than rimmed steel, the use of which is not rec-

Table 1—Properties of Carbon-Steel Plates of Firebox Quality (ASTM A285)

Chemical Analysis:	Grade A	Grade B	Grade C
Carbon, maximum, %			
For plates $^3/_4$ in. and under in thickness	0.15	0.20	0.25
For plates over $^3/_4$ in. to 2 in., inclusive, in thickness	0.17	0.22	0.30
Manganese, maximum, %	0.80	0.80	0.80
Phosphorus, maximum, %			
Acid	0.04	0.04	0.04
Basic	0.035	0.035	0.035
Sulfur, maximum, %	0.04	0.04	0.04
Mechanical Properties:			
Tensile strength, psi.	45,000–55,000	50,000–60,000	55,000–65,000
Yield point, minimum, psi.	24,000	27,000	30,000
Elongation, in 8 in., minimum, %	$\frac{1,550,000}{\text{Tensile strength}}$	$\frac{1,550,000}{\text{Tensile strength}}$	$\frac{1,550,000}{\text{Tensile strength}}$

* ASTM *Specifications for Steel for Bridges and Buildings.*

ommended, particularly for automatic welding because of the detrimental effect on the weld of the numerous segregations.

Table 2—Properties of Carbon-Silicon Steel Plates (ASTM A201)

	Grade A	Grade B
Chemical Analysis:		
Carbon, maximum, %		
For plates 1 in. and under in thickness	0.20	0.24
For plates over 1 in. to 2-in., inclusive, in thickness	0.24	0.27
For plates over 2 in. to 4 in., inclusive, in thickness	0.27	0.30
Manganese, maximum, %	0.80	0.80
Phosphorus, maximum, %	0.035	0.035
Sulfur, maximum, %	0.04	0.04
Silicon, %	0.15–0.30	0.15–0.30
Mechanical Properties		
Tensile strength, psi.	55,000–65,000	60,000–70,000
Yield point, minimum, psi.	0.5 tensile strength	0.5 tensile strength
Elongation, in 8 in., minimum, %	1,550,000 / Tensile strength	1,550,000 / Tensile strength

Although high-strength, low-alloy steels have not been used extensively in the United States for the fabrication of penstocks, the saving in weight that might be effected by the use of such steels for large diameter penstocks and penstocks subjected to high heads or pressures, is a challenge to the designing engineer and it is possible that as our knowledge of the welding of such steels increases, their use will increase. The API-ASME Code lists the following ASTM Specifications as covering steels suitable for unfired pressure vessels:

A204 (Grades A, B and C)—Molybdenum-Steel Plates for Boilers and Other Pressure Vessels.

A212 (Grades A and B)—High-Tensile Strength Carbon-Silicon Steel Plates for Boilers and Other Pressure Vessels.

A225 (Grades A and B)—Manganese-Vanadium Steel Plates for Boilers and Other Pressure Vessels.

The tensile strengths of the above steels range from 65,000 to 82,000 psi. with minimum yield points from 32,500 to 41,000 psi. The maximum carbon content is held to 0.30% or less for plate thicknesses up to 4 in., except for A212, for which it may run slightly higher. Additional strength is imparted to these steels by varying amounts of manganese, molybdenum, silicon or vanadium added to the steel. Although welding experience with the above steels is as yet somewhat limited, it has been found beneficial to preheat the plates that are to be welded and to stress relieve the completed pipe after welding. This applies especially to plates over 1-in. thick, or whose carbon content exceeds 0.30%. The heat treatment will increase the cost of construction and the cost is further increased by the higher price of these steels as compared to the carbon steels. Unless such increased costs are overbalanced by a reduction in plate thickness and weight made possible by the use of higher design stresses for the high strength steels, their use will not be economical.

In addition to the steel plates, various other ferrous materials are used in the construction of penstocks. The structural steel supports for the penstocks are usually fabricated from steel conforming to ASTM *Specifications for Steel for Bridges and Buildings* (Serial Designation A7). Stiffener rings may also be made from this type of steel, which has a minimum tensile strength of 60,000 to 72,000 psi., a minimum yield point of 33,000 psi., and a minimum elongation, in 2 in., of 22%. Flanges for connection to gates, valves or to turbines, are usually made from forged or rolled steel, conforming to ASTM *Specifications for Forged or Rolled Steel Pipe Flanges, Forged Fittings and Valves and Parts for High-Temperature Service* (Serial Designation A105). This steel is made in Grades I and II, with minimum tensile strengths of 60,000 and 70,000 psi., respectively, minimum yield points of 30,000 and 36,000 psi., respectively, and minimum elongations in 2 in., of 25 and 22%, respectively.

The welding electrodes used for manual welding are of the heavy covered type especially designed for all-position welding, in accordance with *Tentative Specifications for Mild Steel Arc-Welding Electrodes*, previously mentioned.

Among the nonferrous metals used in penstock construction there are bronzes and brasses for rocker supports, nickel-cladding and flax packing for expansion joints and other materials, which are described in other sections.

DESIGN

The diameter of a penstock is determined from an economic analysis in which the cost of the penstock is balanced against the value of power lost due to flow in the pipe. Economical velocities have been found to vary from 10 to 20 ft. per sec. depending on head and other variables entering into the problem. The diameter resulting in the lowest annual cost, including depreciation, value of power lost and fixed charges, is the most economical to use.

The efficiency of arc-welded joints varies according to the type of joint and the weld inspection used. For the longitudinal joints of penstocks which are subjected to the full operating head, either double-welded butt joints or single-welded butt joints with backing strips are used. This is because butt-welded joints provide the most efficient connection, not only in strength and impact resistance, but also hydraulically. The API-ASME Code specifies a joint efficiency of 80% for pipe made from firebox quality steel with butt-welded joints, which is increased to 90% if the longitudinal joints are radiographed. Some designers favor the use of joint efficiencies of 90 and 100%, respectively, for unradiographed and radiographed welds. (A 100% joint efficiency may also be used if the pipe containing the joint in question is subjected to a hydrostatic pressure test at a minimum pressure equal to 150% of the total operating head, including water hammer.) In view of recent advances made in welding, particularly with automatic equipment, the higher efficiencies are believed to be more appropriate. The API-ASME Code specifies an increase in joint efficiency of 5% if the pipe is stress relieved in accordance with the code. Although stress relieving is beneficial in reducing the residual stresses due to welding, especially for very heavy plates or for steels of high-carbon content and the low-alloy steels, it is not generally used for carbon steels except in special cases.

Pressure rises due to water hammer are produced by the rapid closure of the turbine gates and can be computed for simple conduits in accordance with standard formulas or charts developed for that purpose. Under certain operating conditions, as with oncoming loads, the turbine gates will open rapidly and subnormal pressures may develop in the penstock. These may also result from pressure oscillations due to surges or when the water column parts and rejoins abruptly in the penstock. To prevent a possible collapse of the penstock under such conditions, it may be necessary to adjust its profile or to reinforce the shell with stiffeners at critical points along the profile. The impact loads due to surge conditions make it desirable to use ductile materials which will absorb the abnormal stresses by yielding, thus avoiding rupture in the plates and welds. The scope of this chapter does not permit a full discussion of water hammer phenomena, which are treated in special publications.

The design of support rings for large self-supporting steel pipe is based on the elastic theory of thin cylindrical shells. The pipe shell is subjected principally to beam and hoop stresses and the loads are transmitted to the support rings by shear. Pipes adequately reinforced for the bending moments at the points of support may be carried on long spans without intermediate stiffeners. If with or without expansion joints penstocks are continuously supported at a number of points, the bending moment at any point along the penstock may be computed by assuming that it is a continuous beam, using applicable beam formulas.

The length of the span to be used is a matter of economy. Very long spans, say over 75 ft., are usually not economical as the plate thicknesses must be increased and heavy support rings used at the supports to carry the increased bending moments due to beam action. The design of support rings is treated in special publications. In areas subjected to seismic disturbances, the supports should be designed for a horizontal force of 0.1 to 0.2 of the gravity load depending on the severity of earthquake shocks reported for the area.

A typical support ring consisting of two 6 by $^3/_4$-in. steel bars is shown in Fig. 14. The rings are welded to the pipe shell with two continuous fillet welds and are tied together with diaphragm plates. Two support columns made from 8-in. wide flange beams are welded between the rings with fillet welds and plug welds to carry the pipe and water load to the rocker supports and concrete piers. The pipe may also be provided

with box-shaped ring girders and supported directly on saddle-type concrete piers lined on top with embedded steel plates, using graphited asbestos sheet packing between girder and liner to reduce friction.

Changes in profile or alignment of a penstock are effected with fabricated segmental bands, using small deflection angles to reduce hydraulic losses due to flow.

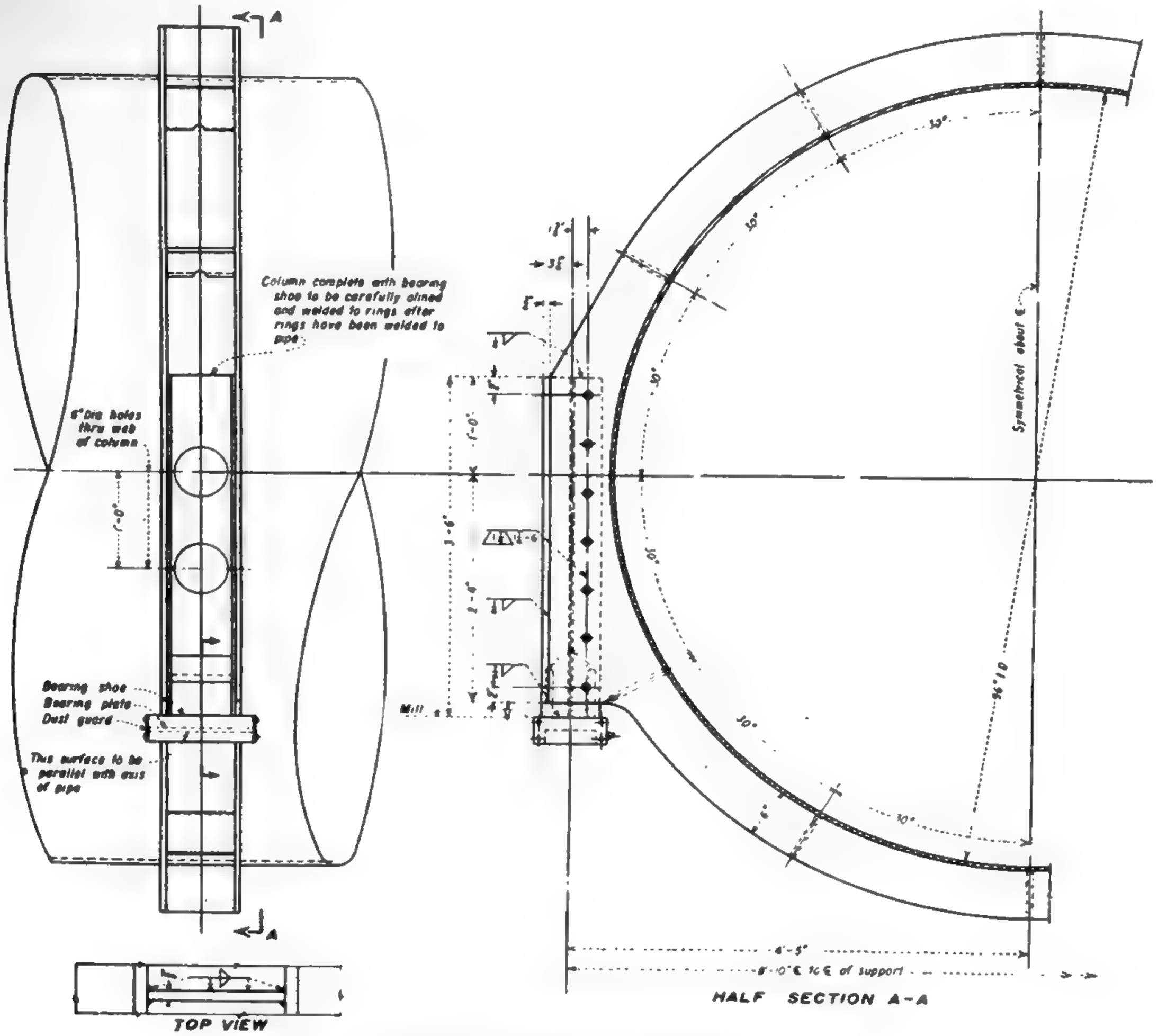
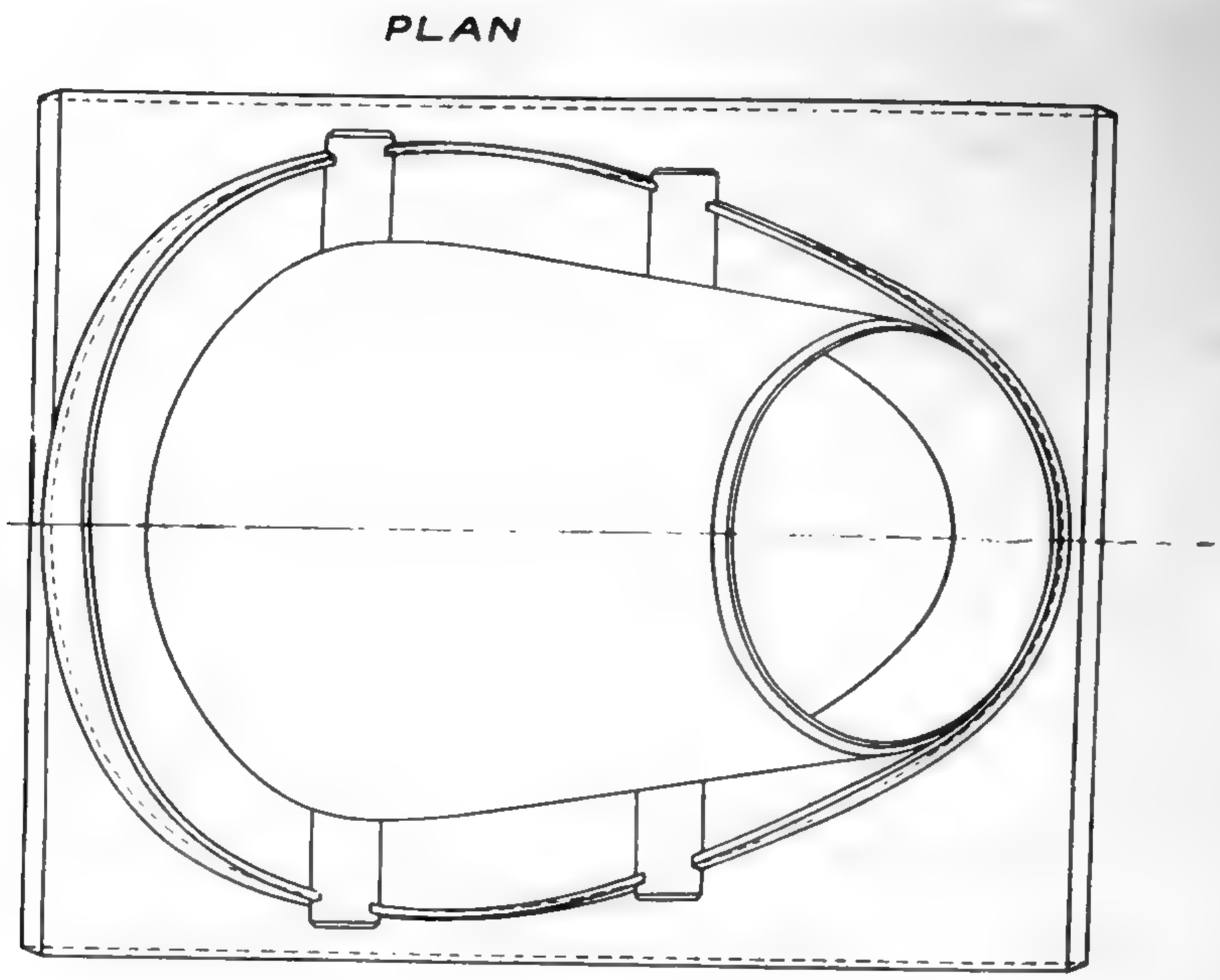


Fig. 14.—Typical Support Ring for 96-In. Diam. Pipe

Bends may be of constant diameter or they may be formed as reducing bends in which the diameter is reduced in the downstream direction.

When a penstock header supplies two or more turbines or is diverting a portion of the flow to an irrigation line, branch outlets or wye connections are used between the main line or header and the branch pipe. Such branch outlets or wye connections require special reinforcements to compensate for the metal removed for hydraulic reasons. Figure 15 shows a branch outlet on a 102-in. diam. penstock. The branch outlet is of conical shape and diverts a portion of the flow to a 50-in. diam. branch pipe leading to an outlet valve which controls irrigation release. The intersection of the branch pipe with the penstock is provided with a curved T-beam, which is reinforced with two 6-in. diam. tie bolts welded to the beam at both ends.

Exposed penstocks are subjected to atmospheric temperature changes when empty, and to the temperature of the water when in operation. If fully restrained against movement, the temperature variations will produce a unit stress equal to the coefficient of expansion times the



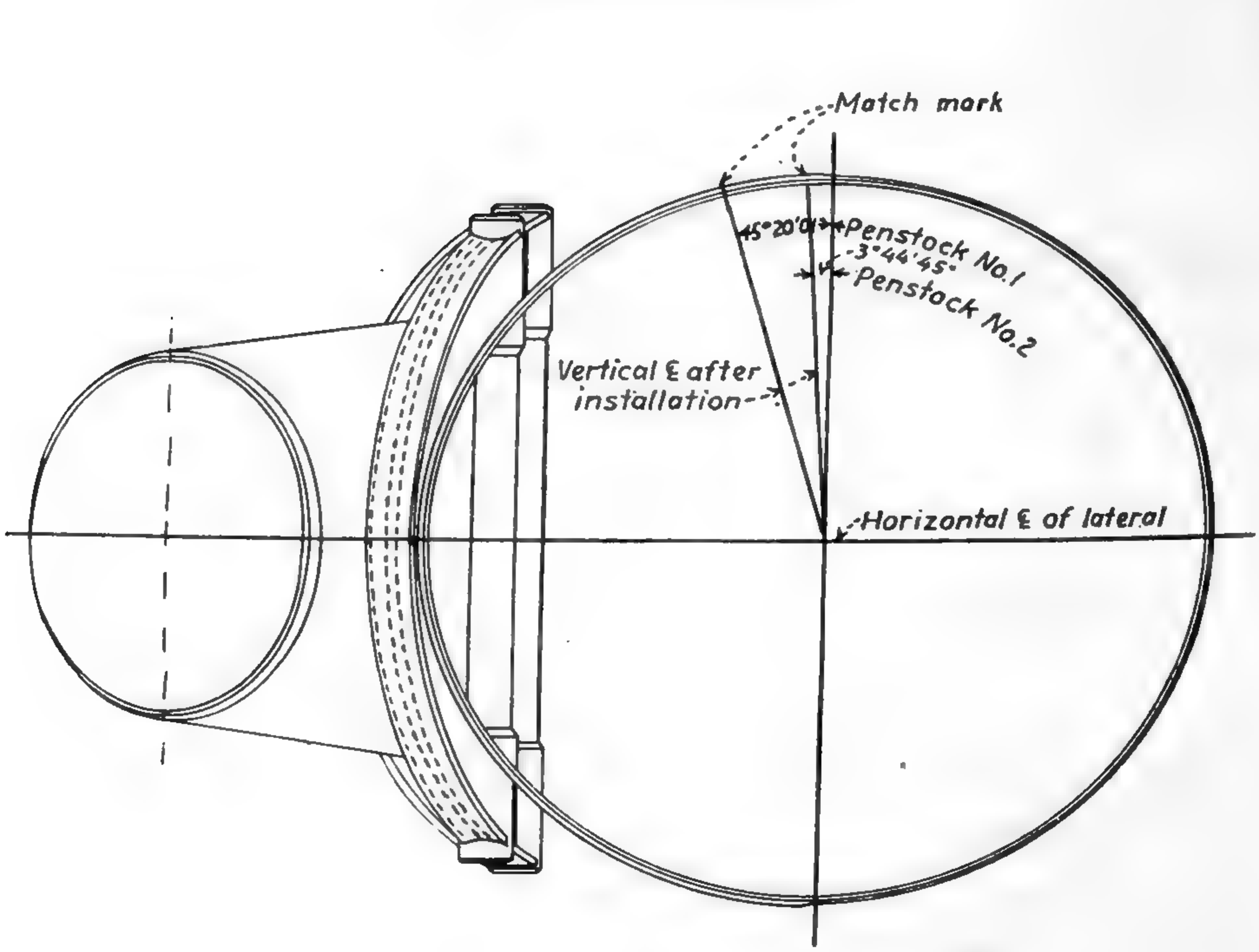


Fig. 15.—Branch Outlet for 102-In. Diam. Penstock

modulus of elasticity of the steel, or 195 psi. per °F. temperature change. In order to permit free movement and prevent excessive temperature stresses in exposed penstocks, expansion joints are provided. There are several types of expansion joints, among which the sleeve-type is the most generally used. Figure 16 shows a typical all-welded sleeve-type expansion joint for a 96-in. diam. steel penstock. The packing consists of several rings of square, braided flax, compressed with a packing gland and takeup bolts to make the joint watertight. Where penstocks pass through construction joints separating two concrete masses, as between the dam and powerhouse, provision should be made for movement in both longitudinal and transverse directions. In such cases a so-called double-acting expansion joint is used. This joint permits longitudinal movement due to temperature changes and vertical displacement due to foundation deflection.

Penstocks are usually provided with filling lines, manholes, vents, drains, piezometer connections, service outlets, flanged connections, etc., which must be given special attention in the design

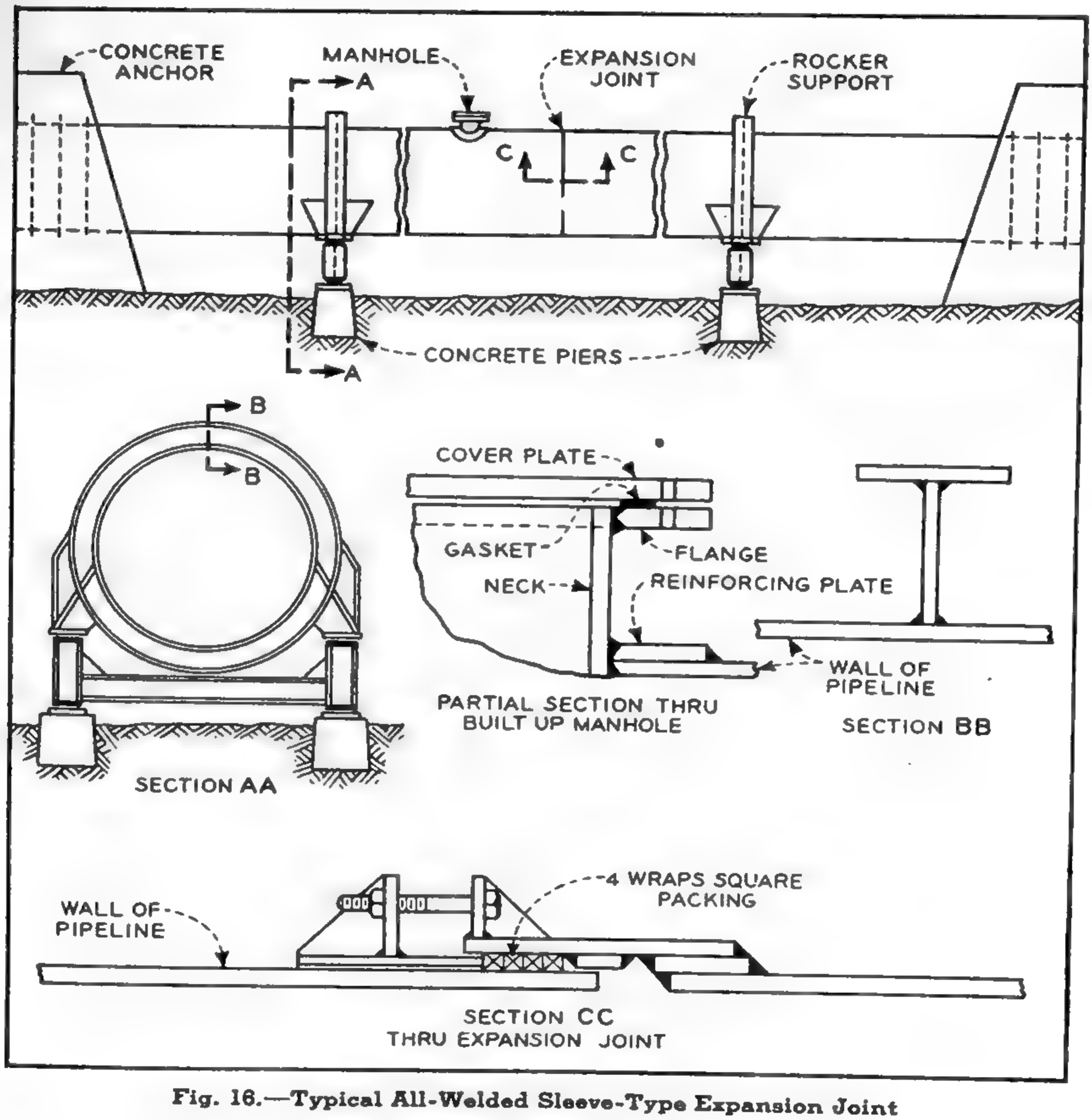


Fig. 16.—Typical All-Welded Sleeve-Type Expansion Joint

Finished openings in the pipe shell exceeding 2 in. in diam. must be reinforced as required by the code to prevent concentrations of stress.

WORKMANSHIP

Fabrication and Erection

Transportation problems usually determine whether welded plate-steel penstocks should be fabricated in a contractor's shop

or at the site of installation. As rail transport of pipe exceeding 12 ft. in diam. is not feasible, such sizes are either completely fabricated in the field, or the plates are cut to size, the edges prepared for welding, and rolled in the shop, then shipped for completion in the field. The fabrication of penstocks includes a number of special operations performed on such equipment as plate rolls, presses, oxygen-cutting equipment, welding machines, stress-relieving equipment, testing machines, radiographic and handling equipment. In addition, blasting and coating equipment is used for the coating of the completed pipe.

penstocks where possible. For irregular circumferential joints and for joints which are to be welded in place during erection, automatic welding is not well adapted and manual welding is used. Heavy plates for manually field-welded joints are usually provided with double-vee-grooves for plates up to about $1^1/_2$ in. thickness and with double-U grooves for thicker plates. For automatic welding the plates should be provided with single-vee or double-vee grooves, depending on weld backing or plate thickness, which also determine the diameter of the welding electrode, the amperage, voltage and the welding speed to be used.

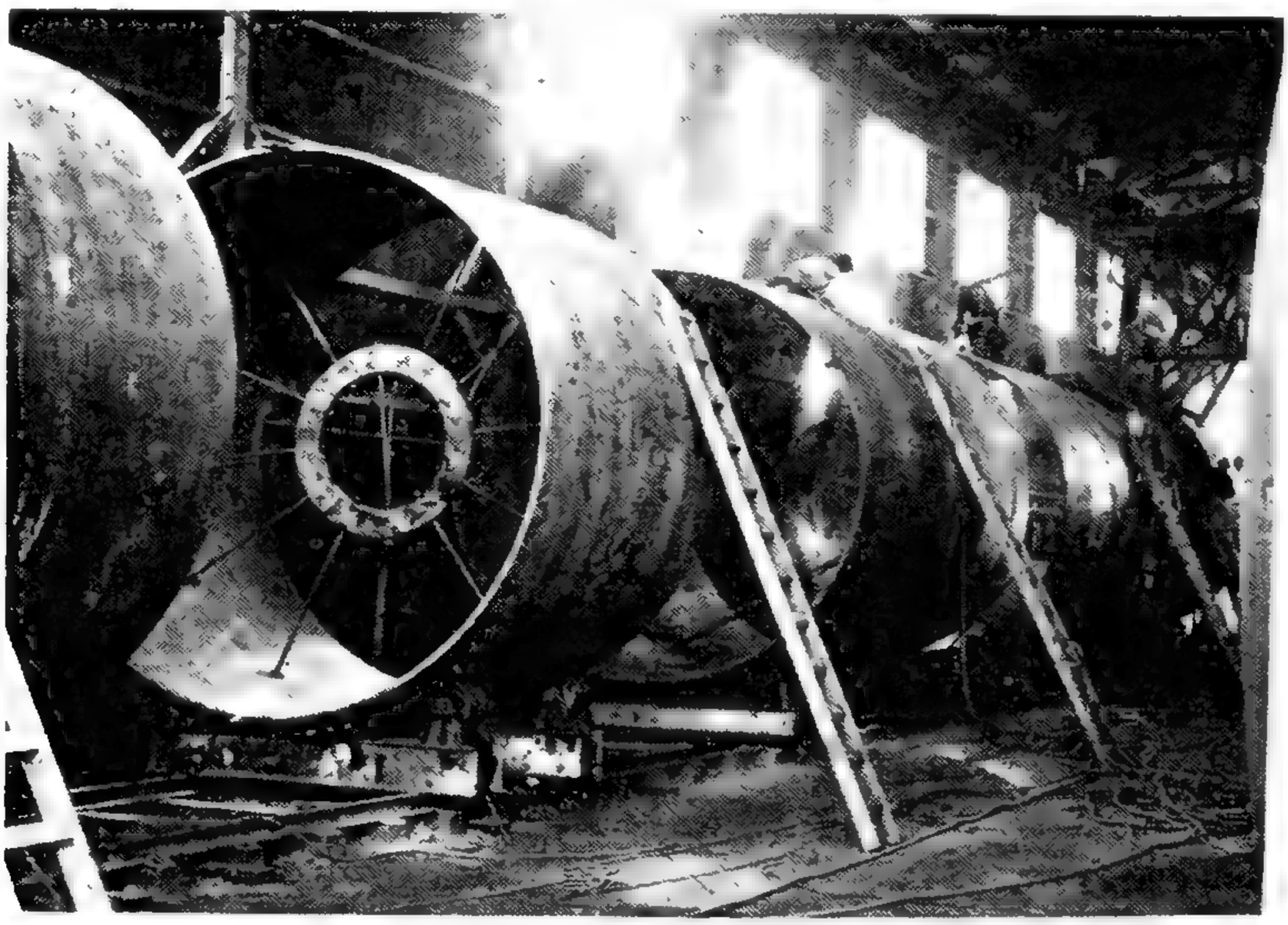


Fig. 17.—Pipe Courses for 15-Ft. Diam. Penstock

As plates of the desired size and thickness for large penstocks are rarely available from supply houses, they are usually ordered to the required size and thickness from the steel mill, allowing for extra length and width for trimming. Upon arrival in the shop, the plates are oxygen-cut, or sheared and planed, to exact width and length and the edges prepared for welding. The preparation of the plate edges depends on the welding process to be used. Welds of more uniform quality can be produced with automatic submerged arc welding than with manual welding, as full control can be maintained of the welding speed and current. Therefore, this type of welding is used on

After the plates are cut to size and prepared for welding, the edges are first pressed to shape on a plate press, then the plates are rolled into pipe courses the length of which is equal to the plate width. Depending on their diameter, the pipe courses are made from one or more plates, with one or more longitudinal joints. After rolling, the longitudinal seams are welded on the automatic welding machine, completing a pipe course. Two or more pipe courses are then welded into pipe sections or laying lengths of 20 to 40 ft. long. For long runs of pipe the accumulated weld shrinkage in girth joints should be taken into consideration. Extra material, usually about $^1/_8$-in. per

joint for manual welds and $^{1}/_{16}$-in. for automatic welds, should be added to the theoretical width of plates to offset this shrinkage and obtain pipe sections and runs which will fit actual field surveys. Figure 17 shows some pipe courses and sections for a 15-ft. diam. penstock during fabrication. The length of pipe sections is dependent on plate width, loading economy, the capacity of testing machines or handling equipment. Sheared carbon-steel plates are usually rolled in thicknesses from $^{3}/_{16}$ to 2 in., and in widths from 24 to 148 inches. For some types, as carbon-silicon steel, plates up to 6-in. thick are rolled. Welding economy indicates the use of steel plates of the greatest width practical; however, the cost of plates increases rapidly with an increase in width. Therefore, both welding and plate costs should be considered in determining the economical width to be used in penstock fabrication.

Arc welding on penstocks requires a continuous supply of electric current of proper voltage and of ample amount. Either d.c. or a.c. may be used, the former being the more common. Direct current may be furnished from large motor generator sets with the motor arranged for any commercial power supply.

Electrodes of the heavy covered type should be used. Among the various electrodes, mild steel electrodes conforming to Classification E6010 are the most extensively used type for all-position welding for pipes, tanks and other steel structures which require considerable welding in the vertical and overhead positions. Electrodes of Classifications E6012, E6013, E6020 and E6030 are also extensively used.

When a pipe section is completely welded, the joints are inspected by radiography, trepanning, pressure testing or whatever other manner is specified.

Cracks, incomplete fusion and undercuts are not acceptable. The acceptability of porosity, slag inclusions and cavities should be determined from the size and distribution of the defects or by comparison with an ASME standard set of radiographs. Unacceptable defects should be removed and the welds repaired and inspected again to prove the quality of the repair welds. Figure 18 shows the X-raying of a circumferential seam in the shop. (See Chapter 42 for further information on radiography and other inspection methods.)

A high carbon content or larger thickness, or a combination of these, may make it advisable to preheat the steel prior to welding and then stress relieve the completed section. A preheat temperature of 200 to 300°F. should be applied by

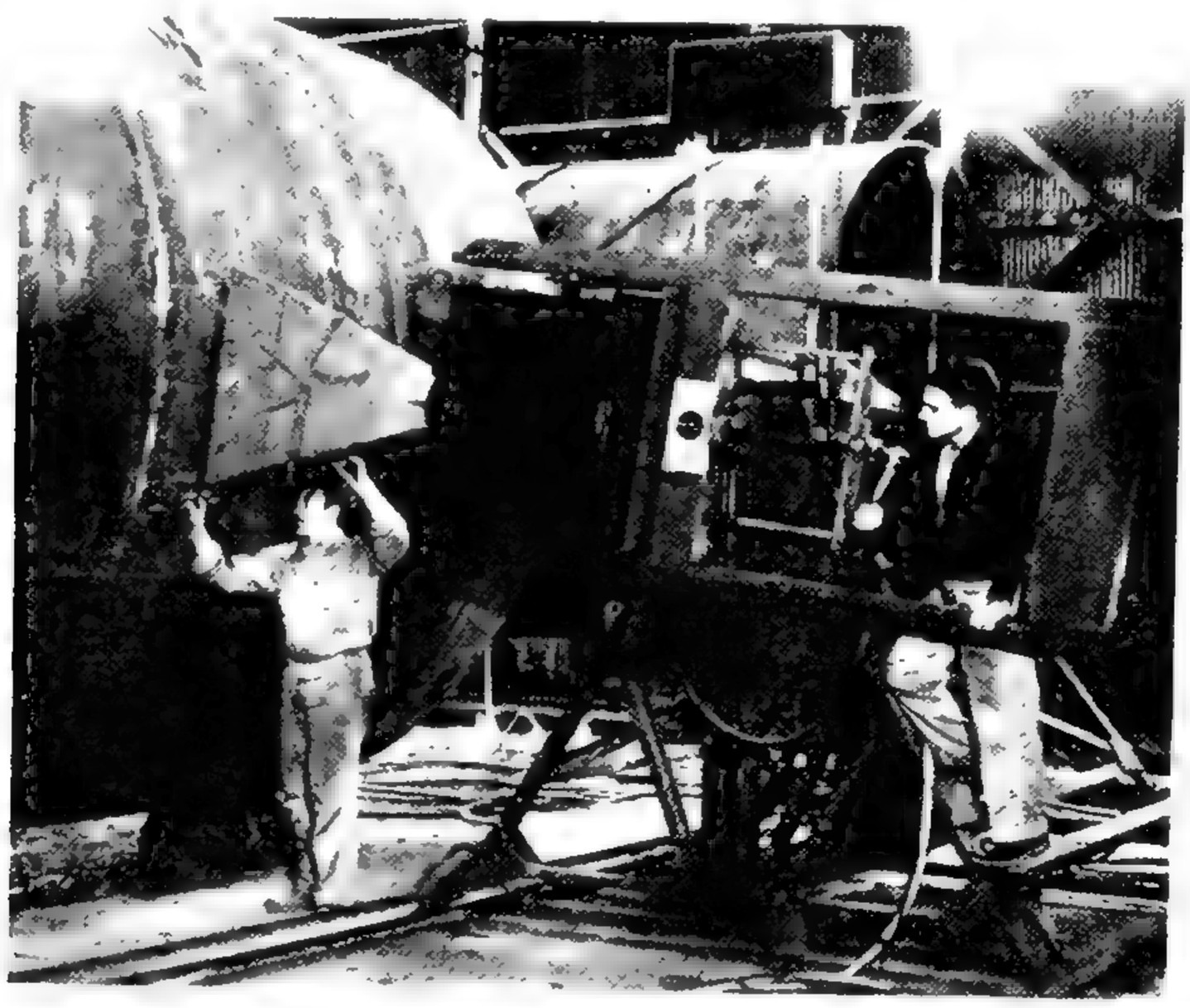


Fig. 18.—X-Ray Inspection of Circumferential Pipe Joint

torch or with gas burners prior to welding. In stress relieving, a temperature of between 1100 and 1200°F. should be maintained for 1 hr. per inch of metal thickness, then the section should be cooled in the stress-relieving furnace or in still air to below 600°F. at a rate not exceeding 500°F. per hr. divided by the maximum thickness. Peening may also be done to control distortion and decrease any cracking tendency. Thermal stress relieving should be performed after all welding has been completed. All sections that have been repaired by welding should again be stress relieved after the weld repairs have been completed. (See Chapter 43 for further discussion on peening and stress-relief heat treatment.)

on prepared supports in accordance with marking diagrams furnished by the pipe fabricator, fitting the sections together and complete welding of the joints. Figure 21 shows the installation work in progress for five 15-ft. diam. penstocks at Shasta Dam.

The quality of field work is dependent on the accuracy of shop fabrication. Proper edge preparation for welding, and accurately formed plates and pipe sections of proper length, if protected against deformation during handling and shipment, will facilitate field installation work. The welding is limited generally to girth joints and must be performed in position. The fitting of field joints prior to welding is important. On the top half the pipe

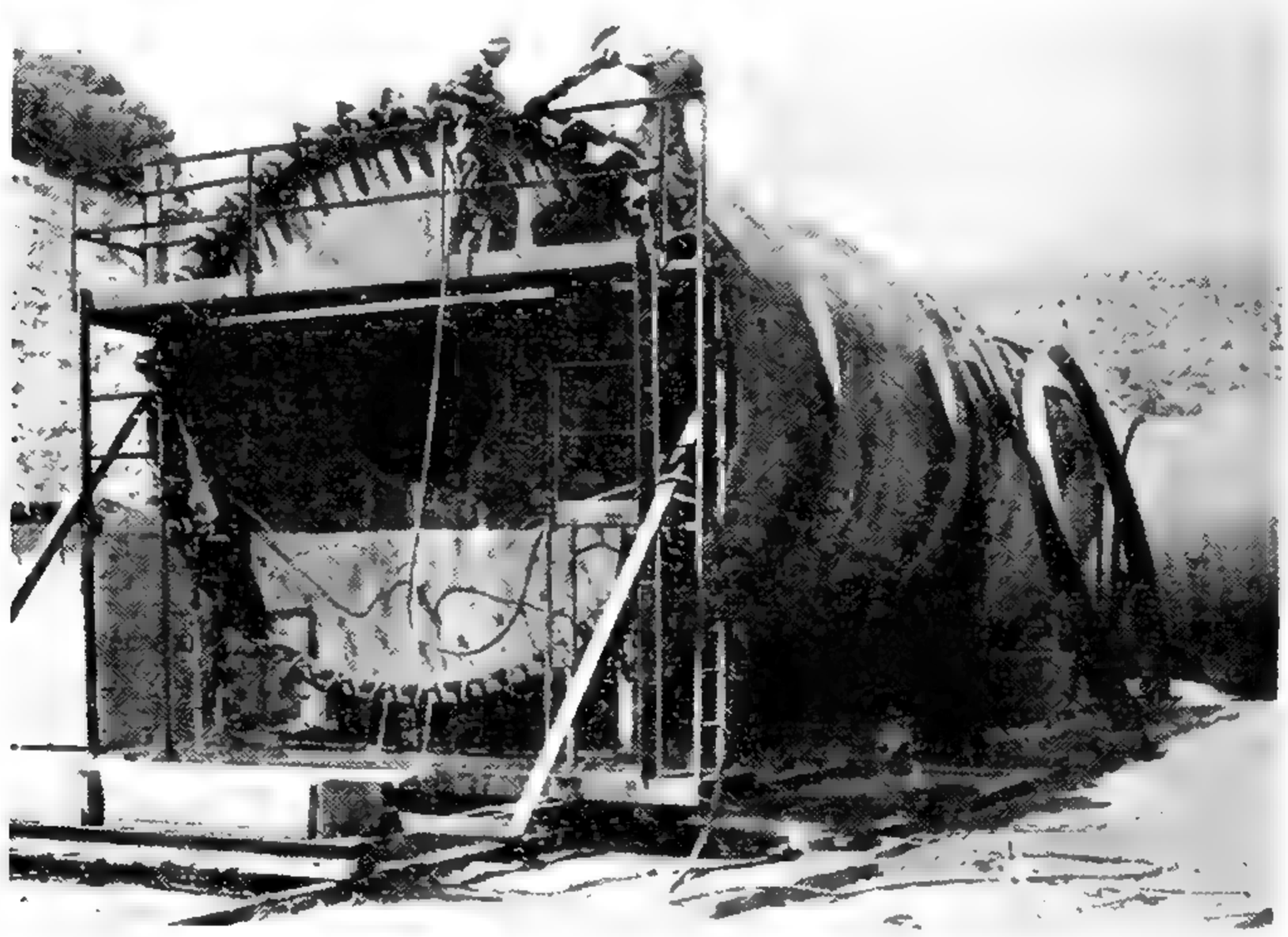


Fig. 19.—Hydrostatic Testing of Pipe Section

After stress relieving, the pipe sections may be tested on a hydrostatic testing machine as shown in Fig. 19 or by the attachment of bulkheads, using a test pressure of $1^1/_2$ times the operating pressure including water hammer. In some cases this pressure test of individual penstock sections may be replaced by a proof hydrostatic test on the installed penstock, which is preferable as it includes all welded joints.

The installation of penstocks involves problems of handling as shown in Fig. 20 where a cableway was used, then setting the marked pipe sections to line and grade

ends may be fitted from the outside and on the bottom half from the inside, using temporary fitting lugs welded at intervals across the joint as shown in Fig. 22. All fitting lugs are on the top side of the joints leaving the overhead side fully accessible for the first weld deposits. The actual welding of a girth joint may be accomplished with two welders, one stationed on the inside and one on the outside of the pipe, as outlined in Fig. 23. Making the first pass using a backstep sequence and welding uphill in opposite quadrants simultaneously will help to maintain the root opening and insure uniform shrinkage

in the joint. When two complete layers of weld metal have been deposited in the overhead position, the fitting lugs on the top side can be removed and the joints backchipped. The balance of the welding is then completed. Chipping should be done with round-nosed tools until all visible defects are removed.

All field welding is performed manually using electrodes of the heavy-covered type for all-position welding. The sections to be welded should be accurately matched and retained in position during welding by the use of expanding spiders on the inside of the pipe or by exterior butt straps permitting all welding to be performed from the inside of the pipe. This latter practice may be necessary in tunnels having limited clearance around the pipe which would make welding from the outside impracticable. Wherever possible, however, all joints should be welded from both sides of the joint. Weld metal originally deposited at the bottom of the weld groove should be chipped or flame gouged to obtain a clean surface for the deposit of the first bead from the opposite side of the joint. Tack welds, unless made in a manner which facilitates their inclusion in the final weld, should be removed so that they will not become a part of the final joint. The weld metal should be deposited in successive layers and each layer should be thoroughly cleaned to base metal before applying the next layer. A weld reinforcement not exceeding $^1/_8$ in. should be used. Peening of weld deposits is not required except in special cases when necessary to compensate for weld shrinkage. The completed weld must show complete penetration, without undercutting or other imperfections. When welding in cold weather it is advisable to preheat the plates prior to welding. All unacceptable defects found by visual inspection, trepanning, radiography or pressure-testing, should be removed by chipping, gouging or grinding, and the resulting cavities refilled with weld metal in the same manner as the original grooves were filled. Weld repairs should be reradiographed or re-

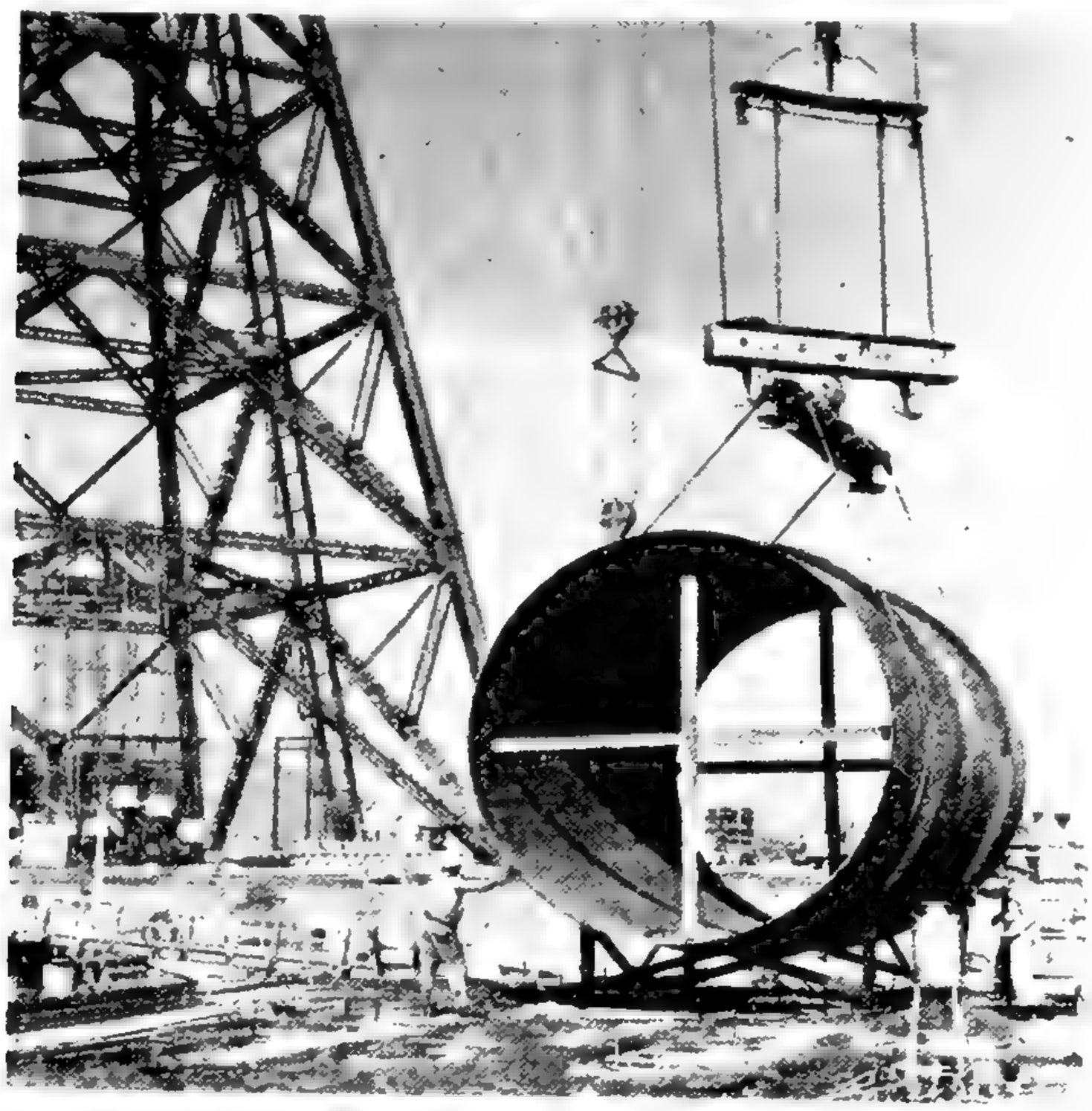


Fig. 20.—Installation of 15-Ft. Diam. Sections at Shasta Dam

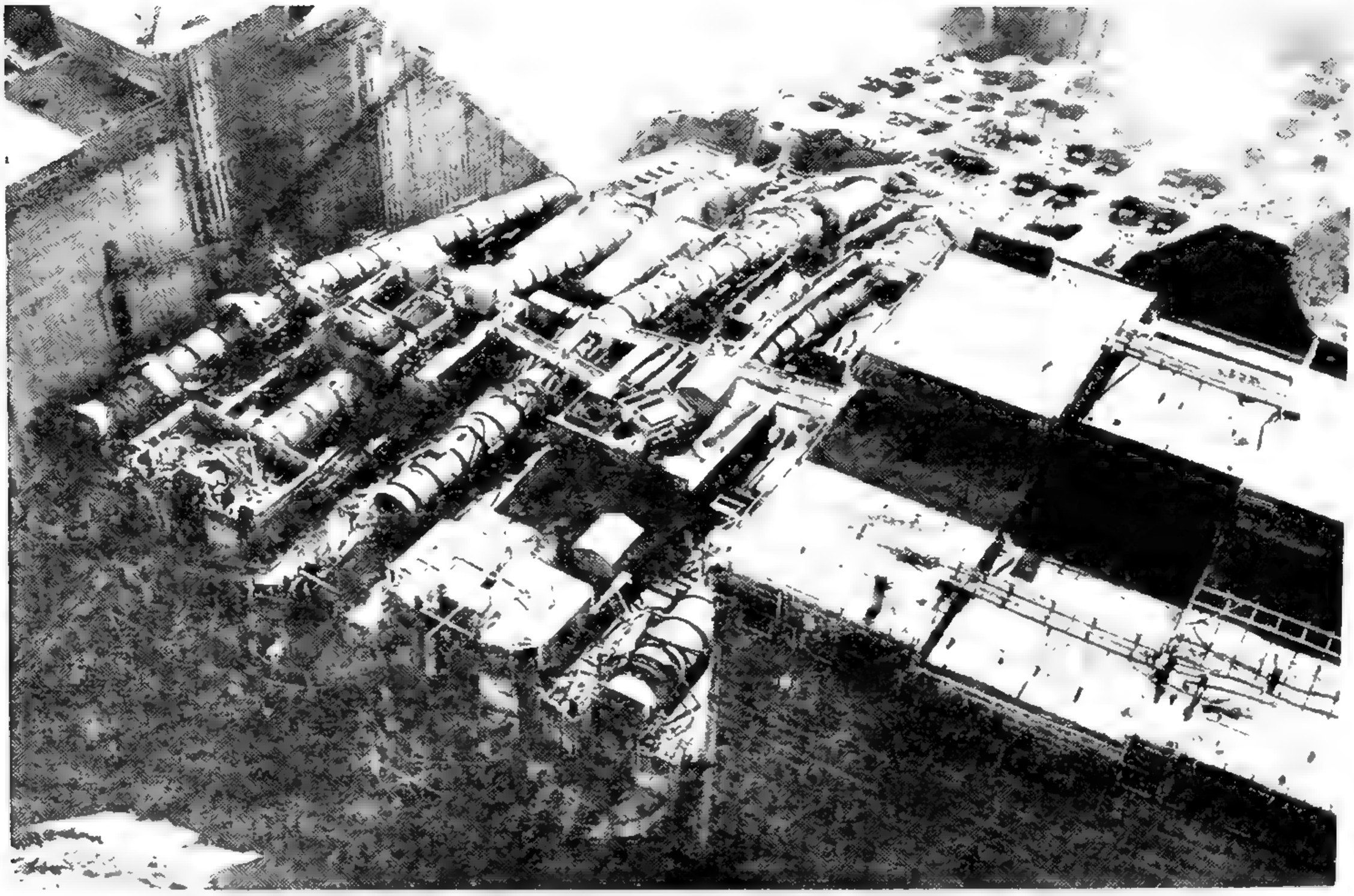


Fig. 21.—Penstocks at Shasta Dam

tested as required to prove the quality of repairs. For penstocks requiring radiographic inspection of circumferential joints welded in place during installation, portable radiographic equipment is used.

INSPECTION AND TESTING

If required by the purchaser, the welding procedure to be used by the penstock fabricator should be qualified in accordance with the *Standard Qualification Procedure* of the American Welding Society. This includes reduced-section tension, free-bend, root-, face- and side-bend tests for groove welds, and fillet-weld-soundness, and longitudinal and transverse shear tests for fillet welds.

All welding on penstocks must be performed by welders who have passed qualification tests in accordance with the *Standard Qualification Procedure* of the AMERICAN WELDING SOCIETY. The tests for groove welds include root-, face- and side-bend tests; and for fillet welds, fillet-weld soundness tests in each of the differ-

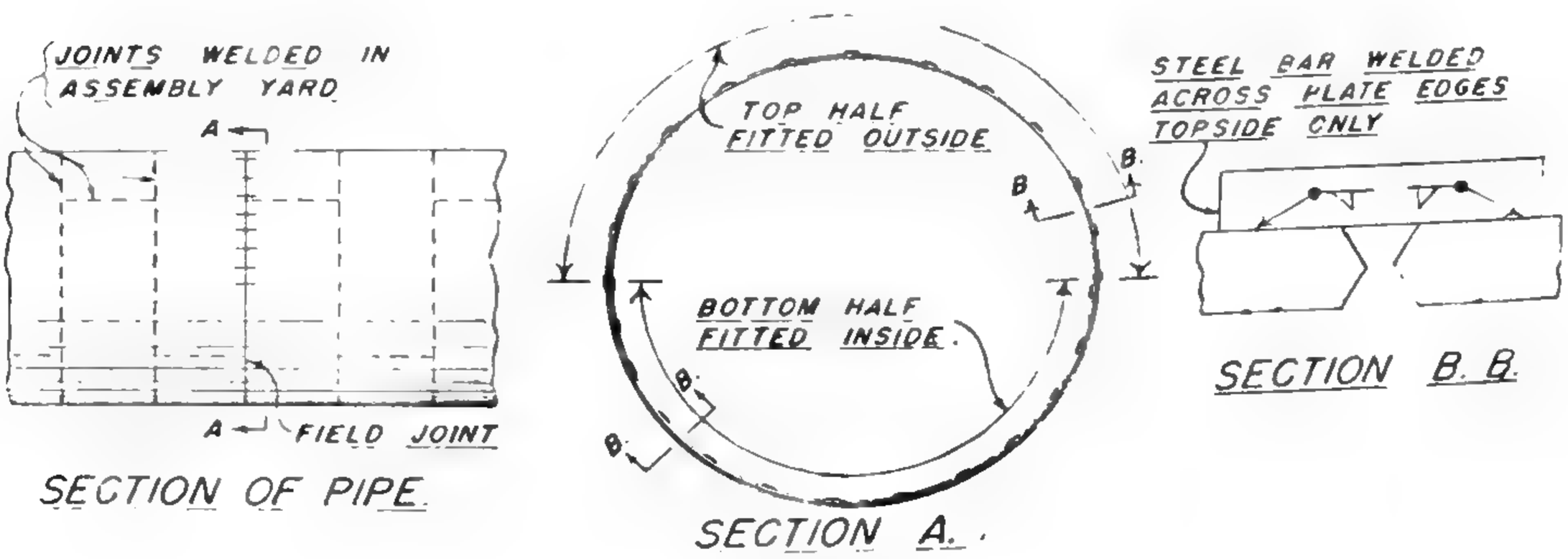


Fig. 22.—Method of Fitting Field Joints

ent positions of welding for which the welder is to be qualified, such as flat, horizontal, vertical and overhead positions.

A check on the quality of production welding is maintained by the requirement that one test plate is to be prepared for a certain amount of completed length of seam as follows:

	Linear Feet
For plate under 1/2 in. in thickness	300
For plate 1/2 in. to 1 1/4 in. in thickness	200
For plate over 1 1/4 in. in thickness	100

Test plates should be of the same material and of approximately the same thickness as used for the penstock. The edge preparation, electrodes and welding procedure used for the test plates should also be the same as used for the penstock.

All fabrication, testing and installation work on penstocks should be subject to rigid inspection by qualified welding inspectors to assure construction in accordance with the specification requirements. All radiographs and trepanned plugs should be examined by the inspector to determine the acceptability of the welds and the extent of repairs. The inspector should witness the preparation of test plates and, when possible, the testing of specimens, in connection with all procedure and welder qualifications, and production tests. The hydrostatic pressure test of each penstock section, or the proof hydrostatic test of the complete installation should also be witnessed by the inspector; likewise, all cleaning and coating operations on the pipe. A complete record of all inspections and of all weld repairs should be maintained, the films marked with identification numbers and shipped to the project office for safekeeping in order to have a record in case of failure. The inspector should check the tolerances in pipe joints, expansion joints or other features which will affect field installation and fitting.

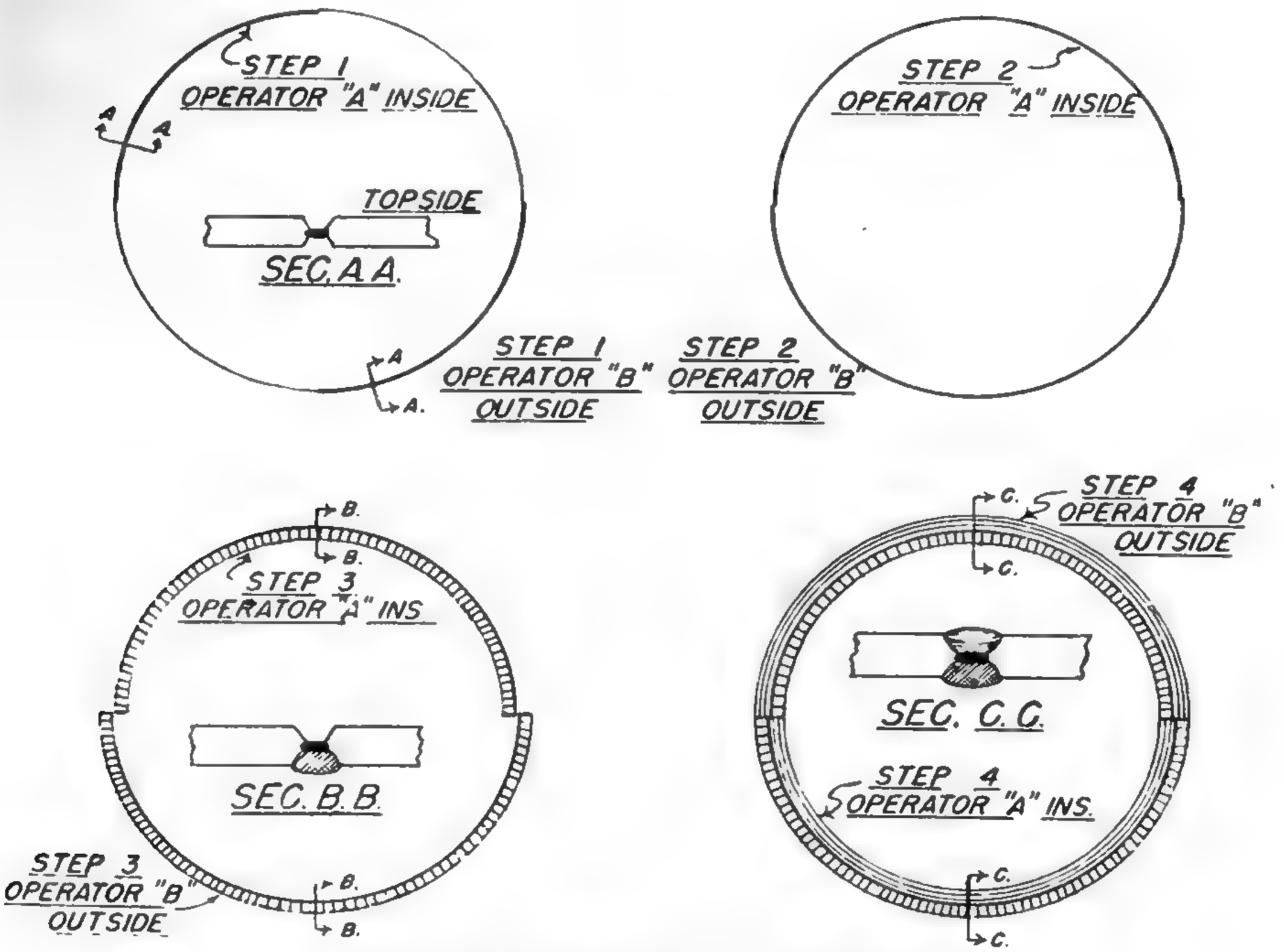


Fig. 23.—Welding Sequence for Field Joints

Circumferential joint welded in position by welders *A* and *B*.

BIBLIOGRAPHY

1. *Comparison and Limitations of Various Waterhammer Theories,* R. S. Quick, Mechanical Engineering, May 1927.

2. *Electrically Welded Steel Water Pipe,* W. H. Powell, The Canadian Engineer, November 4, 1930.

3. *Design of Large Pipelines,* Herman Schorer, Transactions of the American Society of Civil Engineers, September 1931.

4. *All Electrical Arc-Welded Steel Penstock,* C. M. Allen, The Welding Journal, February 1933.

5. *Welded Steel Pipe Line of the Panther Valley Water Co.,* Farley Gannet, The Welding Journal, February 1933.

6. *Welded Joints Reduce Friction Losses in San Francisquito Steel Penstock,* Construction Methods, February 1933.

7. *Symposium on Waterhammer,* ASME Hydraulic and ASCE Power Divisions, June 1933.

8. *Welding a Large Water Pipe Line at Vancouver, B.C.,* W. H. Powell, The Canadian Engineer, October 31, 1933.

9. *Penstocks for Boulder Dam,* C. M. Day and Peter Bier, Mechanical Engineering, August 1934.

10. *Welding 78-In. Steel Supply Line for Seattle Water Department,* G. W. Desellem, Engineering News-Record, August 16, 1934.

11. *Electric Welding Owyhee Siphons,* Construction Methods, May 1935.

12. *The Bouquet Canyon Dam and Inlet—Outlet Pipe,* W. W. Hurlbutt, Journal of the American Water Works Association, August 1935.

13. *Report on Steel Pipe Lines for Underground Water Service,* Special Investigation 888, Underwriters' Laboratories, Inc., 1936.

14. *Building Steel High Pressure Pipe Line on Aqueduct System,* Southwest Builder and contractor, July 17, 1936.

15. *Steel Pipe 11 1/2 Feet in Diameter Welded by Improved Methods,* Engineering News, May 20, 1937.

16. *A Method of Determining Wall Thickness of Steel Pipe for Underground Service,* R. E. Barnard, Journal of the American Water Works Association, June 1937.

17. *Large Delivery Lines for the Colorado Aqueduct System,* Julian Hinds, Civil Engineering, July 1938.

18. *Colorado Aqueduct Distribution System,* Julian Hinds, Journal of the American Water Works Association, January 1939.

19. *Welding Steel Pipe in Sub-Zero Temperatures,* G. H. Garrett, The Welding Journal, April 1939.

20. *Installation of a 54-In. Steel Intake Line,* E. P. Stewart, Journal of the American Water Works Association, May 1939.

21. *New High Pressure Steel Water Supply Line for Colorado Springs,* E. L. Mosley, Journal of the American Water Works Association, August 1940.

22. *Standard Specifications for Electric Fusion Welded Steel Water Pipe of Sizes up to But Not Including 30 Inches,* Am. Water Works Association, 1941.

23. *Code for Pressure Piping (ASA B31),* Am. Society of Mechanical Engineers, 1942.

24. *Fittings and Specials for Steel Pipe,* R. E. Barnard, Journal of the American Water Works Association, October 1942.

25. *Formulas for Stress and Strain,* R. J. Roark, McGraw-Hill, 1943.

26. *Field Welding of Steel Water Pipe,* H. Arthur Price and G. H. Garrett, Journal of the American Water Works Association, October 1943.

27. *Steel Siphon Rehabilitation on the Los Angeles Aqueduct,* W. W. Hurlbut, B. S. Grant and H. A. Price, Journal of the American Water Works Association, November 1943.

28. *Outline of Design Factors for Steel Water Pipe Lines,* R. E. Barnard, Journal of the American Water Works Association, January 1944.

29. *Piping Handbook,* Sabin Crocker, 1945.

30. *Texas Gas for California,* A. F. Bridge, The Oil and Gas Journal, September 21, 1946.

31. *Pipe for the Biggest Inch,* F. M. Burt, The Welding Journal, July 1947.

32. *Special Features of Trunk Mains Laid in Philadelphia,* J. E. Gill, Water Works Engineering, November 26, 1947.

33. *Design Standards for Steel Water Pipe,* R. E. Barnard, Journal of the American Water Works Association, January 1948.

34. *Conversion of Pipe Lines from Oil to Gas Transmission,* B. D. Goodrich, Mechanical Engineering, September 1948.

35. *Design of Long-Span Self-Supporting Steel Pipe,* G. H. Garrett, Journal of the American Water Works Association, November 1948.

36. *Tentative Standard Specifications for Field Welding of Steel Water Pipe Joints,* American Welding Society, (D7.0)—American Water Works Association (7A.8), 1949.

37. *Welded Steel Penstocks, Design and Construction,* Engineering Monograph No. 3, P. J. Bier, U.S. Bureau of Reclamation, 1949.

CHAPTER 57

INDUSTRIAL PIPING*

INTRODUCTION

FOR THE PURPOSES of this chapter, the components of welded industrial piping systems are considered to be: (1) pipe or tubing; (2) welding end valves; (3) welding fittings; (4) welding flanges; (5) backing or welding rings; (6) electrodes and welding rods. Parts such as bolts, gaskets, hangers and insulation are not considered herein, since they are common to all piping systems whether welded or not.

Both ferrous and nonferrous materials are currently being utilized in welded piping systems. Ferrous materials considered in this chapter are: (1) carbon steel and wrought iron; (2) low-alloy steel; (3) medium-alloy steel; (4) high-alloy steel. Nonferrous materials considered are: (1) copper and copper alloys; (2) nickel and nickel alloys; (3) aluminum and aluminum alloys; (4) lead.

GOVERNING CODES AND SPECIFICATIONS

Scope of Regulatory Codes

Design and construction of welded piping systems for industrial installations should comply with existing codes and specifications, all of which are written on the basis of minimum requirements for safety. Certain applications, however, may require more conservative design and construction precautions than stipulated in these codes. For instance, a particular application may necessitate extra allowance for corrosion or erosion, lower stresses than specified due to a requirement of minimum distortion or creep, X-ray or gamma-ray inspection of all joints where the penalty for a leak is extraordinary.

The American Standard *Code for Pressure Piping (B31.1)* deals particularly with minimum safety requirements for the selection and designation of dimensional standards, materials, design, fabrication, erection and testing of piping systems. The principal purpose of the Code is to serve as a guide to state and municipal authorities in drawing up their regulations; also to serve architects, engineers, equipment manufacturers and erectors as a standard of reference with respect to pressure piping. The Code is composed of seven sections: Power Piping, Gas and Air Piping, Oil Piping, District Heating Piping, Refrigeration Piping, Fabricating Details and Material Identification.

The ASME *Boiler Construction Code*, which also covers piping connected with boilers, is the only Code which has been legally recognized and made mandatory by state and municipal authorities. Where so recognized, compliance is prerequisite to acceptance of the installation by the States and Insurance Companies. There are nine sections in the Code, of which the following have references to industrial piping:

(*a*) Section I, Power Boilers, formulates minimum specifications for the construction of piping directly connected to steam power boilers within prescribed limits. Where specific rules are not given in other sections, the rules in Section 1 may be used.

(*b*) Section VIII, Unfired Pressure Vessels, contains rules and computation methods for the attachment of piping to vessels.

There has also been prepared by joint sponsorship, the API-ASME *Code for the Design, Construction, Inspection and Repair of Unfired Pressure Vessels for Petroleum Liquids and Gases*, which includes connecting piping. This Code per-

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* Prepared by a committee consisting of D. H. Corey, Detroit Edison Co., *Chairman;* A. N. Kugler, Air Reduction Sales Co.; J. D. Mattimore, Tube Turns, Inc.; J. Hall Taylor, Taylor Forge & Pipe Wks.; H. Weisberg, Public Service Electric and Gas Co.; C. C. Zimmerman, Benjamin F. Shaw Co.

mits more liberal design factors than Section VIII of the Boiler Code consistent with oil refinery practice, but as a safeguard this Code includes a mandatory inspection and repair schedule.

Procedure and Welder Qualification

It is now a generally accepted fact that in order to obtain a satisfactory welded piping installation it is necessary to first establish and qualify a definite welding procedure and, second, qualify the necessary welders to carry out that procedure. The procedure should cover base metal specifications, preparation of welding ends, filler metal, welding technique, preheat and postheat temperature.

A satisfactory procedure having been established, the quality of welding will then depend on the ability of the welder working under proper supervision. Codes for qualification of procedure and operators are as follows:

The AWS *Standard Qualification Procedure,* published as a separate pamphlet, is also contained in Chapter 60 of this HANDBOOK. Part I relates to the method of qualifying a contemplated welding procedure and Part II to the method of qualifying welders under a satisfactory given procedure. The rules apply to both manual arc- and gas-welding processes.

The *ASME Boiler Construction Code, Section IX,* contains the same subject matter for application to piping as the AWS *Standard Qualification Procedure,* except that reference is made to ASME (ASTM) Material Specifications.

The American Standard *Code for Pressure Piping (B31.1)* contains in Appendix I a form of the AWS *Standard Qualification Procedure,* modified with special reference to piping.

The Heating, Piping and Air Conditioning Contractors National Association has formulated standard welding procedures for manual metal arc and oxy-acetylene welding of pipe. The National Certified Pipe Welding Bureau is an affiliate of this Association, having as its purpose the administration of welder qualification tests in a uniform manner in accordance with the Association's standard procedures, and the interchange of qualified welders between contractors who have adopted the standard procedures, without the necessity of retesting them.

When procedures and welders have been qualified under Section IX of the ASME *Boiler Construction Code,* such interchange of qualified welders, between employers following identical welding procedures, is acceptable for piping work within the scope of that Code.

The National Board of Boiler and Pressure Vessel Inspectors was organized to administer uniformly the rules of the ASME Boiler Code. It is composed of chief inspectors of States and Municipalities which have adopted the Boiler Code. A pamphlet issued by the National Board entitled *Recommended Rules for Repairs by Fusion Welding to Power Boilers and Unfired Pressure Vessels* (over 15 pounds pressure) makes reference to seal welding and repairs to boiler tubes and pipe of low-carbon steels of known weldable quality and having a carbon content of less than 0.35%. For welding alloy steel, reference is made to the ASME Code. Appendices are included relating to welder qualification tests. No repairs by welding may be made without an inspector's approval.

General Recommendations for High-Alloy and Nonferrous Materials

All of the above codes deal almost exclusively with piping of carbon and low-alloy steel. While the ASME *Boiler Construction Code* and the ASA *Code for Pressure Piping* publish allowable working stresses which may be utilized for determining the minimum permissible thickness of some high alloy and copper, nickel and aluminum pipe, the designer, in general, must depend on the principles set forth in these codes governing welded steel piping systems for guidance. In the case of procedure and welder qualifications, it is strongly recommended that the same *type* of qualification procedure be followed for high alloy and nonferrous piping as that which is mandatory for materials specifically covered by the codes.

MATERIALS

A. Ferrous Materials

Material and Dimensional Standards

Dimensional standards, covering carbon steel pipe, cast and forged valves, fittings and flanges, were originally developed on the basis that they would be assembled

into piping systems by means of mechanical joints. During the past twenty years many of these standards have been modified to take cognizance of the use of welding. Entirely new dimensional standards have been developed for butt-welding and socket-welding fittings. These standards provide pressure-resisting fittings equal in strength to seamless pipe with considerable decrease in weight and space requirements over flanged fittings. Complete lines of such fittings, made from seamless pipe, solid forgings or plate, have been developed.

Simultaneous with the development of such dimensional standards by the American Standards Association, ASTM Standards governing the material requirements for pipe, tubing, castings, forgings and flanges for piping were either modified to provide for their use in welded systems or newly created specifically for such use. Both the American Society for Testing Materials and the American Standards Association are currently engaged in formulating new standards covering alloy steel piping components, under a program started in 1930 and somewhat retarded by World War II. The concurrent standardization of electrodes and welding rods for the most part has been carried out without specific reference to their use in welding pipe, but has been helpful.

Weldability

The term weldability is used to generally indicate the relative ease, or difficulty, with which a material can be welded. As characteristics appear which adversely affect weldability, greater precautions must be exercised. In the welding of ferrous piping, the following characteristics should be considered:

1. Any strong tendency of the base metal to crack during the welding operation or while cooling after welding.
2. Any major change in mechanical properties due to the welding operation.
3. Any marked change in the metallurgical structure of the base metal as a result of the welding operation.
4. Changes in chemical composition by volatilization or reaction with air.
5. Formation of refractory coating, making special fluxes necessary.

Carbon steel piping materials in the carbon ranges and thicknesses usually encountered are free from the tendency to crack during or after welding, nor do any significant changes take place in their mechanical properties or metallurgical structure. When the component parts have a thickness of $^{3}/_{4}$ in. or greater, however, there may be some difficulty in obtaining welds free from cracks due to the mass of metal and the greater rigidity of the parts. For this reason, as will be shown below, preheating and stress relief are usually required when wall thicknesses of this order are involved.

Underbead cracking is a factor of hardenability of the steel, which is determined by its chemical composition. In Table Q-5 of Section IX of the ASME *Boiler Code,* some measure of the effect of chemical composition on weldability is found. The simplest carbon steels are grouped in the first section (*P1*) of this table. Their carbon contents are limited to $0.55 - \frac{Mn + Si}{4}$, where Mn and Si are, respectively, the percentages of manganese and silicon. The third section (*P3*) of the table contains another group of steels with higher maximum contents of carbon and manganese, and with carbon limited to $0.65 - \frac{Mn + Si}{4}$.

A parenthetical note states that experience has indicated the advisability of preheating up to 350° F. when welding materials in this group. No comparable rules or suggestions are found in other portions of Table Q-5 dealing with alloy steels. However, Pars. P-108 and P-112 of Section I of the *Boiler Code* require that welded joints be stress relieved by uniformly heating to at least 1100° F., and up to 1200° F. (or higher if this can be done without distortion) for all materials. Different temperatures may be used to obtain proper stress relief as required by the characteristics of the metal. The only exceptions to this requirement are that carbon steel and carbon molybdenum steel (when the latter contains not more than 0.20% C) need not be stress relieved when the wall thickness is $^{5}/_{8}$ in. or less.

On the other hand, the following specific requirements regarding preheat and stress relief are contained in Pars. 627 and 628 of the Code for Pressure Piping:

Preheating to 400° F. is required for welded joints

(*a*) in carbon steels containing more than 0.35% carbon when the wall

thickness is 1/2 in. or greater (this combination is rarely found in welded pipe systems);

(*b*) for all thicknesses of carbon-molybdenum steel piping.

Stress Relief at 1100 to 1250° F. is required (except where heat treatment for reasons other than stress relief requires a higher temperature)

(a) for all carbon steels 3/4-in. thick or thicker;

(*b*) for all carbon steels containing in excess of 0.35% carbon regardless of thickness;

(*c*) for carbon-molybdenum steels when the wall thickness is 1/2 in. or greater.

Some carbon molybdenum steel pipe has been found to be susceptible to *graphitization*, the precipitation of free carbon in the form of graphite nodules or flakes, when subjected to prolonged service at temperatures of the order of 900 to 950° F. The reasons for varying degrees of susceptibility are not yet clearly understood, but it is believed that deoxidation practice, forming, subsequent heat treatment and welding influence the extent of the occurrence of graphitization. Its most serious form is a segregation of graphite particles at the extremity of the area affected by the heat of welding. It is now generally believed that either a normalizing treatment consisting of heating at 1725° F. for 2 hr., followed by slow cooling (300° F. per hr.) to 800° F., or stress relief at 1300° F. for 4 hr., will retard, if not prevent, the serious type of graphitization. It is further believed that the normalizing treatment described above will partially, though not completely, restore the mechanical properties, particularly the ductility, of welded joints in which segregation of graphite has begun but has not progressed to a serious degree. (For more detailed information consult recent volumes of ASME *Transactions*.) It is believed that carbon molybdenum steel pipe will not graphitize to any serious extent within the usual service temperature limits.

Alloy steels (for which no specific rules exist), with the exception of the austenitic stainless steels, almost invariably require preheat and stress relief in order to avoid cracking during the welding operation or subsequently due to the combined effect of their air-hardening properties and residual welding stresses.

The need for preheating, and even more important, for postheat treatment is particularly evident in the case of the chromium bearing steels of the medium and high alloy groups, with the possible exception of the 5% chromium grade when stabilized by titanium or columbium addition. See also Chapter 30, Chromium Irons and Steels. (These stabilizers also have the effect of materially reducing the air-hardening tendency of this steel.) Steels having a chromium content ranging from 4 to 14% with little or no nickel, are decidedly air-hardening and, in addition, have suppressed transformation points (400 to 700° F.) when cooled from welding heat. This means that their greatest shrinkage, when cooling, takes place at a temperature when the metal is no longer sufficiently plastic to absorb such shrinkage without extremely high residual stresses being created. Of all the steels used in welded piping these are probably the most susceptible to cracking during cooling. Ideally, welded joints in these materials should be maintained uniformly at a temperature above 700° F. during the welding operation. Immediately after completion of the weld, the entire assembly should be put in an annealing furnace, the temperature raised to 1550 to 1650° F. and allowed to cool slowly to below 400° F. If the higher mechanical properties obtainable by normalizing are desired, the material may be withdrawn from the furnace after uniformly attaining a temperature of at least 1550° F. and allowed to cool slowly in still air. If furnace heat treatment is not practical, local stress relief at a temperature of 1300 to 1400° F. may be used. It is important, when such local stress relief is used, that the heated area be slowly cooled to at least 400° F. Local stress relief, if performed at proper temperatures, decreases the hardness of the weld zones, improves the ductility and relieves the stress. Present available evidence indicates that local stress relief will not result in increased hardness at the edges of the heated zone.

Straight chromium steels containing more than 14% chromium fall into two distinct classes, those containing 14 to 18% chromium and those containing 18 to 30% chromium. Both are known as ferritic types, being completely ferritic at all temperatures. When welded they are subject to excessive grain growth, resulting in brittleness and reduced impact

strength at room temperature. Refinement of grain structure cannot be effected by heat treatment, but stress relief does improve ductility and remove shrinkage stresses.

Preheating at 200 to 400° F. is desirable for 14 to 18% chromium steels. Stress relief should be performed at 1400 to 1450° F. followed by slow cooling to 1000° F. This need not follow immediately after welding.

Steels containing 18 to 30% chromium are generally not preheated since this seems to increase the extent of the area in which grain growth occurs. After welding they should be heated to 1600 to 1650° F. for not less than 1 hr. per in. of thickness, and then cooled rapidly to obtain maximum ductility. When welded with 25–12 or 25–20 chromium-nickel filler metal, which is frequently employed in welding high chromium steels in an effort to obtain ductile welds, stress relief at 1450 to 1500° F. gives somewhat better results.

Stress relief of 5 and 9% nickel steels is carried out at temperatures ranging from 1050 to 1100° F. in order to avoid the lower critical temperature of these metals, which have a transformation point at 1200° F. or slightly higher.

The mechanical properties of the chromium-nickel steels used in piping are not affected by heat treatment. However, those which do not contain stabilizing elements, such as columbium, are subject to carbide precipitation as a result of heating through the range of 800 to 1600° F. which occurs during welding. Since heat treatment of piping assemblies to put the carbides back in solution is difficult and expensive, stabilized steels are usually employed when carbide precipitation would result in decreased life of the material. Nevertheless when stainless steels are to be used for high-temperature service, even with stabilizing elements, it is common practice to employ a stabilizing heat treatment consisting of a long-time soaking at 1550 to 1600° F. to disperse the carbides. There has been a limited use of very low carbon (0.03% max.) stainless steel either to minimize carbide precipitation in the unstabilized steels or to reduce the amount of columbium required for stabilization.

See also Chapter 31, Austenitic Chromium-Nickel Steels.

Material Designation and Composition

Tables 1*a* and 4*a* list the names, ASTM specifications and composition of the steels in common use as piping materials. In addition, these tables show the form of the component in which the material is available or is occasionally used. Composition and form available are also given for some steels serving an important but limited use for which ASTM standards have not yet been developed.

General Usage, Service Temperature Limitations and Welding Requirements

Tables 1*b* to 4*b* parallel Tables 1a to 4*a* and summarize the service conditions to which the various steels are generally applied, the temperature ranges over which they are *normally* used, the filler metals and the preheat and stress relief temperatures generally used. The filler metals are indicated by AWS-ASTM designations where such apply and otherwise by the names by which they are generally known.

Allowable Working Stresses and Pressures

The ASME *Boiler Code* and the ASA *Code for Pressure Piping* establish the allowable working stresses for piping at temperatures up to 1200 and 1000° F., respectively. The allowable stresses in the *Code for Pressure Piping* are dependent also upon the service use. Each of the sections of this Code has its own tables of allowable stresses for the different materials.

Butt-welding and socket-welding fittings conforming to ASA B16.9, and B16.11, respectively, must have a bursting strength equal to the theoretical bursting strength of the pipe with which they are used. Hence it is permissible to use the same working stresses as for the pipe in determining their allowable working pressures.

Allowable working pressures at different temperatures for valves and flanges for welding into piping systems are published in the American Standard for *Steel Pipe Flanges and Flanged Fittings* (ASA B16e).

In applying those materials for which the codes give working stresses, the permissible temperature will be governed by

Table 1a—Properties of Carbon Steel Piping Materials

Name or Standard Type Number	ASTM Specifications No.	Grade	Form[a]	Chemical Composition, % Carbon	Manganese	Silicon	Phosphorus	Sulfur
Low carbon	....	....	P, FF	.....	.....	.....	.....	.....
AISI C1022	....	....	P, F, FF, FV	0.18 0.23	0.70 1.00	.....	0.05 max.	0.05 max.
Wrought iron	A72	....	P, FF	.....	0.05 max.	.....	.....	.....
Medium carbon	A120	....	P, FF	.....	.....	.....	.....	.....
Medium carbon	A53	....	P, FF	.....	.....	.....	0.045-0.11	.....
Medium carbon	A106	A[b]	P, FF	0.25 max.	0.30–0.90	0.10 min.	0.04 max.	0.06 max.
	A106	B	P, FF	0.30 max.	0.35–1.00	0.10 min.	0.04 max.	0.06 max.
Medium carbon	A135	A[b]	P, FF	.....	.....	.....	0.045 max	0.060 max.
	A135	B	P, FF	.....	.....	.....	0.045 max	0.060 max.
Medium carbon	A105	I[b]	F, FV	0.35 max.	0.90 max.	0.30 max.	0.05 max.	0.05 max.
	A105	II	F, FV	0.35 max.	0.90 max.	0.30 max.	0 05 max.	0.05 max.
Medium carbon	A181	I[b]	F, FV	0.35 max.	0.90 max.	0.30 max.	0.05 max.	0 05 max.
	A181	II	F, FV	0.35 max.	0.90 max.	0.30 max.	0.05 max.	0.05 max.
Carbon and carbon moly	A234	[c]	FF	.....	[c]	[c]		.....
Medium carbon	A216	WCA	CV, CF	0.25 max.	0.70 max.	0.60 max.	0.05 max.	0.06 max.
	A216	WCB	CV, CF	0.35 max.	0.70 max.	0.60 max.	0.05 max.	0.06 max.

[a] P, pipe; F, forged fittings; FF, wrought fittings; FV, forged valves; CV, cast valves; CF, cast fittings.

[b] These grades differ in their mechanical properties, Grade B and Grade II, respectively having higher strength than Grade A and Grade I, thus permitting higher allowable working stresses.

[c] This specification covers Factory Made Wrought Carbon-Steel and Carbon-Molybdenum Steel Welding Fittings. See ASTM A106, Table 1*a*, and ASTM A206 Gr. P1, Table 2*a*, for appropriate composition.

Table 1b—Welding and Service Conditions for Carbon Steel Piping

Name or Standard Type Number	ASTM Spec. No.	General Use	Service Temperature Limits, °F.	Welding		
				Filler Metal	Preheat, °F.	Stress Relief, °F.
Low carbon	....	Radiant heat and refrigeration coils	—40 to 450	E6010, GA60	None	None
AISI C1022	....	Sub-zero service	—20 to —50	E7010, GA65	None	1150–1250
Wrought iron	A72	Mild corrosive service	—20 to 450	E6010, GA60	None	1150–1250
Medium carbon	A120	Low-pressure steam, water, air, etc.	—20 to 450	E6010, GA60	None	None
Medium carbon	A53	Intermediate to high pressure	—20 to 775	E6010, GA60	None	1150–1250[b]
Medium carbon	A106, Gr. A	High pressure and/or high temperature	—20 to 775	E6010, GA60	None	1150–1250[b]
Medium carbon	A106, Gr. B	High pressure and/or high temperature	—20 to 825	E6010, GA60	None	1150–1250[b]
Medium carbon	A135, Gr. A	Low and intermediate pressure	—20 to 750	E6010, GA60	None	1150–1250[b]
Medium carbon	A135, Gr. B	Low and intermediate pressure	—20 to 750	E6010, GA60	None	1150–1250[b]
Medium carbon	A105, Gr. I & II	Intermediate to high pressure	—20 to 825	E6010, GA60	None	1150–1250[b]
Medium carbon	A181, Gr. I & II	Low and intermediate pressure	—20 to 750	E6010, GA60	None	1150–1250[b]
Carbon and carbon moly	A234	[c]	.....	.....	.....	.....
Medium carbon	A216, Gr. A & B	Intermediate to high pressures and/or temperatures	—20 to 825	E6010, GA60	None	1150–1250

[a] It is considered good practice to preheat when 0.30 to 0.35% C is encountered to prevent cracking, especially when low atmospheric temperatures prevail.

[b] Stress relief required only when wall thickness is 3/4 in. or greater; however, stress relieving of 0.30 to 0.35% C material has often to be resorted to in order to pass the welds through the guided-bend test.

[c] This specification covers Factory Made Wrought Carbon-Steel and Carbon-Molybdenum Steel Welded Fittings. See ASTM A106, Table 1*b*, and ASTM A206, Table 2*b*, for appropriate general use.

Table 3a—Properties of High-Alloy Steel Piping Materials

Name or Standard Type Number	ASTM Specifications			Chemical Composition, %[b]							
	No.	Grade	Form[a]	Carbon	Manganese	Silicon	Chromium	Nickel	Molybdenum	Columbium	Other
12 Chromium, Type 410	A296	10	CV, CF	0.15 max.	1.00 max.	1.50 max.	11.5–14.0	1.00 max.	0.50 max.	....	....
13 Chromium, Type 410	A157	C6	CV, CF	0.15 max.	0.75 max.	1.00 max.	11.5–13.5	0.80 max.	0.50 max.	....	....
13 Chromium, Type 410	A268	TP410	P, FF	0.15 max.	1.00 max.	0.75 max.	11.5–13.5	0.50 max.	....	....	....
13 Chromium, Type 410	A182	F6	FV, FF, F	0.12 max.	1.00 max.	1.00 max.	11.5–13.5	0.50 max.	....	....	....
17 Chromium, Type 430	A268	TP430	P, FF	0.12 max.	1.00 max.	0.75 max.	14.0–18.0	0.50 max.	....	....	....
17 Chromium, Type 430	....	...	FV, FF, F	0.12 max.	1.00 max.	1.00 max.	14.0–18.0	....	....	....	....
20 Chromium, Type 442	A296	11	CV, CF	0.30 max.	1.00 max.	1.00 max.	18.0 22.0	2.00 max.	....	....	Copper, 0.90–1.20
21 Chromium, Type 442	....		FV, FF	0.20 max.	1.00 max.	1.00 max.	18.0–23.0	....	....	....	....
21 Chromium, Type 443	A268	TP443	P, FF	0.20 max.	1.00 max.	0.75 max.	18.0–23.0	0.50 max.	....	....	Copper, 0.90–1.25
27 Chromium, Type 446	A268	TP446	P, FF	0.20 max.	1.50 max.	0.75 max.	23.0–30.0	0.50 max.	....	....	Nitrogen, 0.10–0.25
27 Chromium, Type 446	....	...	FV, FF, F	0.25 max.	1.00 max.	1.00 max.	23.0–27.0	1.00 max.	....	....	....
28 Chromium, Type 446	A296	12	CV, CF	0.50 max.	1.00 max.	1.00 max.	26.0–30.0	4.00 max.	....	....	....
18-8, Type 304	A157	C9	CV, CF	0.15 max.	1.00 max.	2.00 max.	18.00 min.	8.00 min.	....	....	....
19-9, Type 304	A296	1	CV, CF	0.08 max.	1.50 max.	2.00 max.	18.0–22.0	8.0–11.0	....	....	....
18-8, Type 304	A312	TP304	P, FF	0.08 max.	2.00 max.	0.75 max.	18.0–20.0	8.0–11.0	....	....	....
18-8, Type 304	A182	F8	FV, FF, F	0.08 max.	2.00 max.	1.00 max.	18–20	8.0–10.0	....	....	....
18-8 Mo, Type 316	A157	C9	CV, CF	0.15 max.	1.00 max.	2.00 max.	18.0 min.	8.00 min.	As agreed	....	....
19-10 Mo, Type 316	A296	4	CV, CF	0.08 max.	1.50 max.	2.00 max.	18.0–22.0	9.0–12.0	2.0–3.0	....	....
18-8 Mo, Type 316	A182	F8m	FV, FF, F	0.08 max.	2.00 max.	1.00 max.	16.0–18.0	10.0–14.0	2.00 min.	....	....
18-8 Mo, Type 316	A312	TP316	P, FF	0.08 max.	2.00 max.	0.75 max.	16.0–18.0	11.0–14.0	2.0–3.0	....	....
18-8 Mo, Type 317	A157	C9	CV, CF	0.15 max.	1.00 max.	2.00 max.	18.0 min.	8.00 min.	As agreed	....	....
18-8 Mo, Type 317	....	...	FV, FF, F	0.08 max.	2.00 max.	1.00 max.	18.0–20.0	11.0–15.0	3.00–4.00	....	....
18-8 Mo, Type 317	A312	TP317	P, FF	0.08 max.	2.00 max.	0.75 max.	18.0–20.0	11.0–14.0	3.0–4.0	....	....
18-8 Cb, Type 347	A157	C9	CV, CF	0.15 max.	1.00 max.	2.00 max.	18.0 min.	8.00 min.	....	As agreed	....
19-10 Cb, Type 347	A296	5	CV, CF	0.08 max.	1.50 max.	2.00 max.	18.0–22.0	9.0–12.0	....	8X Carbon, 1.00 max.	....
18-8 Cb, Type 347	A182	F8c	FV, FF, F	0.08 max.	2.00 max.	1.00 max.	17.0–19.0	9.0–12.0	....	10X Carbon, 1.00 max.	....
18-8 Cb, Type 347	A312	TP347	P, FF	0.08 max.	2.00 max.	0.75 max.	17.0–20.0	9.0–13.0	....	10X Carbon, 1.00 max.	....
25-12, Type 309	A296	7	CV, CF	0.20 max.	1.50 max.	2.00 max.	22.0–26.0	12.0–15.0	....	....	....
25 12, Type 309	....	...	FV, FF, F	0.20 max.	2.00 max.	1.00 max.	22.0–24.0	12.0–15.0	....	....	....
25-12, 25-20, Type 310	....	...	P, FF	0.10 max.	2.00 max.	1.00 max.	22.0–24.0	12.0–15.0	....	....	....
25-20, Type 310	A296	8	CV, CF	0.20 max.	2.00 max.	2.00 max.	23.0–27.0	19.0–22.0	....	....	....
25-20, Type 310 ..	...	...	FV, FF, F	0.25 max.	2.00 max.	1.50 max.	24.0–26.0	19.0–22.0	....	....	....
25-20, Type 310 ..	...	...	P, FF	0.25 max.	2.00 max.	1.50 max.	24.0–26.0	19.0–22.0	....	....	....

[a] P, pipe; F, forged fittings; FF, wrought fittings; FV, forged valves; CV, cast valves; CF, cast fittings.
[b] Compositions are taken from stated ASTM standard except where product form is not covered by ASTM. The AISI type designations are for reference only, where a corresponding ASTM specification is listed.

Table 3b—Welding and Service Conditions for High-Alloy Steel Piping

Name or Standard Type Number	ASTM Spec. No	General Use	Service Temperature Limits, °F.	Welding			
				Filler Metal	Preheat, °F.	Stress Relief, °F.	Anneal, °F.
12 Chromium, Type 410	A296	Corrosion resistance and high temperature service	32 to 800[a, d]	410, 309, 310	400 min.	1400	1550–1650
13 Chromium, Type 410	A157	Corrosion resistance and high temperature service	32 to 1200[d]	410, 309, 310	400 min.	1400	1550–1650
13 Chromium, Type 410	A268	Corrosion resistance and high temperature service	32 to 1200[d]	410, 309, 310	400 min.	1400	1550–1650
13 Chromium, Type 410	A182	Corrosion resistance and high temperature service	32 to 1200[d]	410, 309, 310	400 min.	1400	1550–1650
17 Chromium, Type 430	A268	Corrosion resistance and high temperature service	32 to 700[b, d]	430, 309, 310	400 min.	1400	1450–1550
17 Chromium, Type 430	....	Corrosion resistance and high temperature service	32 to 700[b, d]	430, 309, 310	400 min.	1400	1450–1650
21 Chromium, Type 442	A296	Corrosion resistance and high temperature service	32 to 700[b, d]	442, 309, 310	None	1600–1650	1600–1650
21 Chromium, Type 442	....	Corrosion resistance and high temperature service	32 to 700[b, d]	442, 309, 310	None	1600–1650	1600–1650
22 Chromium, Type 443	A268	Corrosion resistance and high temperature service	32 to 700[b, d]	443, 309, 310	None	1600–1650	1600–1650
27 Chromium, Type 446	A268	Corrosion resistance and high temperature service	400 to 1400[c]	446, 309, 310	None	1600–1650	1600–1650
27 Chromium, Type 446	....	Corrosion resistance and high temperature service	400 to 1400[c]	446, 309, 310	None	1600–1650	1600–1650
27 Chromium, Type 446	A296	Corrosion resistance and high temperature service	400 to 1400[c]	446, 309, 310	None	1600–1650	1600–1650
18 8, Type 304	A157	Corrosion resistance and sanitary service	0 to 800[c]	308, 347	None	None	1950–2100
19-9, Type 304	A296	Corrosion resistance and sanitary service	0 to 800[c]	308, 347	None	None	1950–2100
18-8, Type 304	A312	Corrosion resistance and sanitary service	0 to 800[c]	308, 347	None	None	1950–2100
18-8, Type 304	A182	Corrosion resistance and sanitary service	0 to 800[c]	308, 347	None	None	1950–2100
18-8 Mo, Type 316	A157	Corrosive, low and high temperature service	−320 to 1500	316	None	None	1950–2100
19-10, Type 316	A296	Corrosive, low and high temperature service	−320 to 1500	316	None	None	1950–2100
18-8 Mo, Type 316	A182	Corrosive, low and high temperature service	−320 to 1500	316	None	None	1950–2100
18-8 Mo, Type 316	A312	Corrosive, low and high temperature service	−320 to 1500	316	None	None	1950–2100
18-8 Mo, Type 317	A157	Corrosive, low and high temperature service	−320 to 1500	317	None	None	1950–2100
18-8 Mo, Type 317	....	Corrosive, low and high temperature service	−320 to 1500	317	None	None	1950–2100
18-8 Mo, Type 317	A312	Corrosive, low and high temperature service	−320 to 1500	317	None	None	1950–2100
18-8 Cb, Type 347	A157	Corrosive, low and high temperature service	−320 to 1500	347	None	None	1950–2100
19-10 Cb, Type 347	A296	Corrosive, low and high temperature service	−320 to 1500	347	None	None	1950–2100
18-8 Cb, Type 347	A182	Corrosive, low and high temperature service	−320 to 1500	347	None	None	1950–2100
18-8 Cb, Type 347	A312	Corrosive, low and high temperature service	−320 to 1500	347	None	None	1950–2100
25-12, Type 309	A296	Corrosion resistance and high temperature service	−320 to 1500	309, 310	None	None	1950–2100
25-12, Type 309	....	Corrosion resistance and high temperature service	−320 to 1500	309, 310	None	None	1950–2100
25-12	....	Corrosion resistance and high temperature service	−320 to 1500	309, 310	None	None	1950–2100
25-20, Type 310	A296	Corrosion resistance and high temperature service	−320 to 1500	310	None	None	1950–2100
25-20, Type 310	....	Corrosion resistance and high temperature service	−320 to 1500	310	None	None	1950–2100
25-20, Type 310	....	Corrosion resistance and high temperature service	−320 to 1500	310	None	None	1950–2100

[a] This steel may embrittle above 800° F.

[b] These steels embrittle at service temperatures of 700–1000° F.

[c] These steels are subject to carbide precipitation at temperatures from 800–1600° F. Weldments must be annealed to insure satisfactory service at sub-zero temperatures.

[d] These metals have low impact strength at low temperatures and care must be taken to prevent shock if they are used at temperatures below 32° F.

[e] These steels are embrittled at temperatures between 885 and 1250° F. but are used in catalytic services from 1250-2100° F. (at low working stress) where nickel content would effect reactions.

Table 4a—Properties of Medium-Alloy Steel Piping Materials

Name or Standard Type Number	ASTM Specifications No.	Grade	Form[a]	Chemical Composition, % Carbon	Manganese	Silicon	Chromium	Molybdenum	Tungsten	Nickel
5 Chrome moly	A157	C5A	CV, CF	0.30 max.	1.00 max.	0.75 max.	4.00– 6.50	0.40–0.65 or	0.80–1.25[b]	.....
5 Chrome moly	A158	P5a	P, FF	0.15 max or 0.20 max.	0.30–0.60	0.50 max.	4.00– 6.00	0.45–0.65 or	0.75–1.25[b]	.....
5 Chrome moly	A182	F5	F, FV, FF	0.25 max.	0.60 max.	0.50 max.	4.00– 6.00	0.45 0.65	.....	0.50 max.
5 Chrome moly silicon	A157	C5B	CV, CF	0.30 max.	1.00 max.	0.75-1.50	4.00– 6 50	0.40-0.65 or	0.80–1.25[b]	.....
5 Chrome moly silicon	A158	P5b	P, FF	0.15 max.	0.30-0.60	1.00-2.00	4.00– 6.00	0.45-0.65	.....	.....
7 Chrome molybdenum	A158	P16	P, FF	0.15 max.	0.30 0.60	0.50- 1.00	6.00– 8.00	0.45- 0.65	.....	.....
9 Chrome molybdenum	A157	C12	CV, CF	0.30 max.	1.00 max.	1.00 max.	8.00–10.00	1.10-1.50	.....	.....
9 Chrome molybdenum	A158	P17	P, FF	0.15 max.	0.30-0.60	0.50 1.00	8.00–10.00	0.90–1.10	.....	.....
5 Nickel (SAE 2515)	....	...	P, FF, F, FV	0.17 max.	0.40–0.60	0.20- 0.35	.....	.....	.....	4.75 5 25
9 Nickel	....	...	P, FF, F, FV	0.12 max.	0.30–0.60	0.15 0.30	.....	.....	.....	8.00 10.00

[a] P, pipe; F, forged fittings; FF, wrought fittings; FV, forged valves; CV, cast valves; CF, cast fittings.
[b] Either molybdenum or tungsten may be used.

Table 4b—Welding and Service Conditions for Medium Alloy Steel Piping

Name or Standard Type Number	ASTM Spec. No.	General Use	Service Temperature Limits, °F.	Welding Filler Metal	Preheat °F.	Stress Relief °F.	Anneal, °F
5 Chrome moly	A157	Corrosion resistance and high temperature service	32 to 1100[a]	5 Chrome moly	400–600	1250–1400	1550–1650
5 Chrome moly	A158	Corrosion resistance and high temperature service	32 to 1100[a]	5 Chrome moly	400–600	1250–1400	1550–1650
5 Chrome moly	A182	Corrosion resistance and high temperature service	32 to 1100[a]	5 Chrome moly	400–600	1250–1400	1550–1650
5 Chrome moly silicon	A157	Corrosion resistance and high temperature service	32 to 1150[a]	5 Chrome moly-Si	400–600	1250–1400	1550–1650
5 Chrome moly silicon	A158	Corrosion resistance and high temperature service	32 to 1150[a]	5 Chrome moly-Si	400–600	1250–1400	1550–1650
7 Chrome molybdenum	A158	Corrosion resistance and high temperature service	32 to 1200[a]	7 Chrome moly	400–600	1250–1400	1550–1650
9 Chrome molybdenum	A157	Corrosion resistance and high temperature service	32 to 1200[a]	9 Chrome moly	400–600	1250–1400	1550–1650
9 Chrome molybdenum	A158	Corrosion resistance and high temperature service	32 to 1200[a]	9 Chrome moly	400–600	1250–1400	1550–1650
5 Nickel	....	Sub-zero service and corrosion resistance	—150 to 825	5 Nickel or 25 Cr–20 Ni	400 min.	1050–1100	.....
9 Nickel	....	Sub-zero service and corrosion resistance	—320 to 825	9 Nickel or 25 Cr–20 Ni	400 min.	1050–1100	.....

[a] These metals have low impact strength at low temperatures and care must be taken to prevent shock if they are used at temperatures below 32° F.

the service conditions. The codes or standards are not to be interpreted to mean that the materials may be safely used under all service conditions within the temperature ranges they give, nor that the materials cannot be safely employed beyond these temperature ranges. In selecting materials, the designing engineer should take into account all operating conditions affecting the adequacy of the piping material. When designing for service temperatures beyond those for which the codes have established working stresses, it is advisable to request of the appropriate code-making body a ruling on what allowable working stresses should be employed.

Backing (Welding) Rings

Backing rings, or welding rings, are extensively employed in ferrous piping systems. No dimensional standards exist for such rings although recommended practice is covered in the *Code for Pressure Piping*. Since their use is mainly confined to carbon and low-alloy steel piping, they are generally made of a mild carbon steel having a maximum carbon content of 0.20% and a maximum sulfur content of 0.05%. The latter requirement is especially important since high sulfur in deposited weld metal (which could be created by an excessive sulfur content in such rings) may cause weld cracks. In a few types of service, such as food processing and chemical processing, the requirement of a completely smooth inside surface may prevent the use of backing rings or require their removal after welding. Disturbance to flow and the slight additional pressure loss caused by these rings may be a factor in special cases. (See also page 1356.)

B. Nonferrous Materials

Under the heading of Nonferrous Materials, the metals used in welded piping systems may be grouped as follows:

1. Copper and copper alloys (includes red brass, yellow brass, silicon bronze and copper-nickel.)
2. Nickel and nickel alloys (includes Monel and Inconel.)
3. Aluminum and aluminum alloys.
4. Lead.

Material and Dimensional Standards

While there are a number of ASTM standards covering pipe or tubing for the first three groups, these standards have been created without specific reference to the means used in assembling them into piping systems. ASTM Standard Specifications for *Copper Pipe, Standard Sizes* (B42) and *Standard Specifications for Red Brass Pipe, Standard Sizes* (B43), contain dimensional tables for regular and extra strong pipe which correspond to standard weight and extra-strong iron pipe size and dimensions. ASTM standards also exist for some alloy castings and, in the case of copper alloys, standards specifically intended for use in manufacturing valves and fittings. These standards likewise contemplate the use of mechanical rather than welded joints.

There are no American Standards regulating the dimensions of nonferrous pipe, valves, fittings and flanges other than those for screwed brass fittings and for brass soldered-joint fittings. Since the nickel and aluminum groups are used mainly for corrosion resistance, avoidance of fluid contamination or sanitary reasons, usually under mild conditions of pressure and temperature, the practice has been to construct valves, fittings and flanges to the dimensional standards used by manufacturers of comparable brass components.

Valves of the copper and nickel groups are frequently soldered or brazed into piping systems but are seldom welded. On the other hand, extensive use of welding fittings of all four metal groups is common. In the case of all but lead, such nonferrous welding fittings are often made to the same dimensions as iron pipe size wrought carbon steel butt welding fittings (ASA B16.9). Because of the greater cost of these metals and the relatively mild pressure-temperature service conditions to which they are generally applied, such fittings and the pipe to which they are welded are more commonly made with considerably less wall thickness than their carbon steel counterparts. In other instances, and for the same reasons, tubing having different outside diameters than pipe but with even thinner walls than lightweight pipe and matching fittings are employed. These types of construction generally involve the use of transition pieces or adapters to permit connection to screwed and sometimes to brazed end valves and other pieces of apparatus.

Weldability

General.—Whereas the weldability characteristics of ferrous piping materials are related primarily to their tendency to crack during the welding operation or during the subsequent cooling period, and to a lesser but highly important degree to their state of internal stress as a result of welding, neither of these characteristics is usually of major importance with nonferrous materials. In general, nonferrous metals, unlike some steels, do not tend to harden on cooling in air from the welding temperature, nor do they have suppressed transformations at temperatures below the plastic range, accompanied by appreciable volumetric changes. Thus, even though the ductility of the deposited metal is lower than the base metal, the danger of cracking is usually remote and the residual stress condition not sufficient to warrant concern over possible stress-corrosion effects. Again, in none of the nonferrous piping materials is there any comparable condition to that caused by the welding heat in unstabilized austenitic stainless steels which might bring about carbide precipitation. Hence there is usually no necessity for subsequent stress relief or other heat treatment after welding, except such as may be required by the ASME *Boiler Code.*

Copper and Copper Alloys (see also Chapter 34).—The chemical composition, high heat conductivity and high fluidity, when molten, of copper and copper alloys have considerable bearing on their weldability. Oxygen-bearing, electrolytic or tough-pitch copper is susceptible to oxide embrittlement when welded or heated above 1292° F. in an atmosphere carrying hydrogen, hence it is not usually recommended for arc and gas welding. It can, however, be readily soft soldered and can be brazed provided a silver brazing alloy having a flow point less than 1292° F. is used and the brazing temperature is carefully controlled. Deoxidized copper, or oxygen-free copper, on the other hand, can be satisfactorily gas welded, soldered or brazed in any position. Owing to the high fluidity of molten deoxidized copper, arc and gas welds must be made with suitable backing rings. All-position welding by oxy-acetylene or inert-gas metal-arc welding is possible, but quite difficult. Since piping installations involve all-position welding, soldering or brazing are the processes commonly used. Because of the high heat conductivity of copper, it is usually necessary to preheat when welding large diameter or unusually heavy pipe. Deoxidized or oxygen-free copper pipe and tubing have been standardized. Oxygen-bearing electrolytic or tough-pitch copper seamless tubes are available only on special order and their use is generally discouraged.

Oxy-acetylene welding of red brass and yellow brass can be satisfactorily accomplished in all positions with suitable backing rings. Shielded metal-arc, carbon arc and inert-gas metal-arc welding are not usually employed as the high heat intensity of the arc causes vaporization of the zinc content in the metal and sweating out and oxidation of any lead that may be present. All-position welding of brass is possible using the oxy-acetylene process. However, soldering or brazing are more generally employed. When welding is attempted, preheating of large diameter and heavy wall pipe is usually necessary. Because of adverse experience encountered with dezincification of yellow brass pipe and tubing, red brass has been generally used and yellow brass pipe and tubing are usually available only on special order.

Copper-silicon alloys have a heat conductivity approaching that of steel, and are readily controllable when molten due to a glass-like slag which forms on the surface of the molten pool. They do not have any chemical constituents which easily vaporize, hence they are more easily welded than any of the other copper alloys used in piping. The copper-silicon alloys can be welded by means of the oxy-acetylene, inert-gas metal-arc and carbon-arc processes. Shielded metal-arc welding can also be used if suitable covered electrodes are available. Welds can be readily made in the flat and vertical positions; the overhead position is more difficult. Backing rings are not required although they are sometimes used. Of the process mentioned, inert-gas metal-arc welding is the most popular because of the soundness and ductility of the welds obtained.

The principal copper-nickel alloy used for pipe and tubing is that known as 70–30, in which the numbers indicate the proportions of copper and nickel, respectively. Other cupro-nickels with lower nickel proportions are available. Cupro-

nickel, 70–30, offers superior resistance to the corrosive action of sea water, hence finds its widest use for water pipe and condenser tubes on ships. The most suitable process for welding this alloy is shielded metal-arc welding. Inert-gas metal-arc welding and oxy-acetylene welding, using a special silicon-bearing welding rod have also been used successfully. While 70–30 cupro-nickel is one of the most readily weldable copper-base alloys, cracking due to hot shortness may at times be encountered. Brazing with silver alloys is also utilized extensively. However, care must be exercised to select a brazing alloy with a low flow point to prevent intergranular penetration, which might occur at high temperatures if the base metal happens to contain residual stresses set up during forming, etc.

Nickel and Nickel Alloys (see also Chapter 35).—This group of metals behaves similar to mild carbon steel and can be welded by the same processes that are used for steel, although sometimes with slight modification of the procedures and techniques. Pure nickel has a narrow solidification range and as a result has a tendency to trap gas. The weld metal of nickel and most of its alloys is very sluggish on deposition. In all cases it is necessary to remove any surface oxide, preferably followed by washing with carbon tetrachloride to obtain freedom from porosity. Satisfactory welding of cast Monel to wrought Monel or cast Monel to wrought steel is very difficult, as cracking will often occur in the cast parts; hence, the welding of cast Monel to wrought material should be avoided when possible.

Aluminum and Aluminum Alloys (see also Chapter 32).—This group of metals, from the standpoint of weldability, is characterized chiefly by their low melting points (1075 to 1210° F.), high heat conductivity and fluidity when molten. Thus, training and experience are necessary before production welding should be attempted. While aluminum and aluminum alloys can be joined by any of the commercial welding and brazing processes, those most commonly employed are the inert-gas metal-arc, oxy-hydrogen and oxy-acetylene processes. Aluminum and aluminum alloy piping and tubing are generally supplied in either a work-hardened or precipitation-hardened condition (obtained by cold-working or heat treatment depending upon the alloy) which gives the material greater strength. The welding operation softens the metal for a distance of 1 to 5 times the pipe thickness on either side of the weld and materially reduces the tensile strength in this zone. It is impractical to restore the original strength of fabricated assemblies by subsequent cold work or heat treatment. In spite of this, it is desirable to use cold-worked or heat-treated pipe to obtain increased resistance to denting or bending in handling and erecting. Additionally, there are indications that the bursting strength of pipe joined by circumferential butt welds is not reduced from that of unwelded pipe to the extent that might be expected based on the actual local strength of the joint after welding. Commercially pure aluminum and aluminum alloyed with 5% silicon are the only filler metals presently employed. In the case of the latter, lower ductility of the deposited metal compared with that of the wrought base metal can be expected. Because of the high fluidity of this group of metals, backing rings should be employed wherever possible.

Lead and Lead Alloys (see also Chapter 36).—The satisfactory welding (erroneously called burning) of these metals requires a high degree of manual skill which is acquired only after long practice. This is due to their low-melting temperatures and high fluidity.

The oxy-hydrogen process is in most common use. The oxy-acetylene process is not generally used for wall thicknesses below $^1/_2$ in., as this mixture of gases develops too high a temperature for welding thin sections. Air-hydrogen, air-acetylene, oxy-city gas, etc., may be used but should be avoided if oxy-hydrogen is available.

Provision for adequate ventilation should be made where lead is to be welded in closely confined quarters, to avoid the toxic effects of lead fumes.

Material Designation and Composition

Tables 5*a* to 8*a* list the names, ASTM Specification, if any, and composition of the nonferrous materials in common use as piping materials. The tables also show the form of the component in which the material is available or occasionally used.

Table 5a—Properties of Copper and Copper Alloy Piping Materials

Name or Standard Type Number	ASTM Specifications			Chemical Composition, %								
	No.	Grade	Form[a]	Copper	Tin	Lead	Zinc	Silicon	Nickel	Iron	Phosphorus	Other
Deoxidized copper	B42	....	P, FF	99.90 min.	....	....	....	....	....	....	0.040 max.	....
Deoxidized copper	B75	Type B	P, FF	99.90 min.	....	....	....	....	....	....	0.015–0.040	....
Deoxidized copper, (arsenical)	B75	Type C	P, FF	99.40 min.	....	....	....	....	....	....	0.040 max.	As 0.15–0.50
Red brass	B43	....	P, FF	83.0–86.0	0.15 max.	0.06 max.	Remainder	....	....	0.05 max.	....	....
Steam or valve bronze	B61	....	C, CF	86.0–90.0	5.5–6.5	1.0–2.0	3.0–5.0	....	1.0 max.	0.25 max.	0.05 max.	....
Composition brass	B62	....	C, CF	84.0–86.0	4.0–6.0	4.0–6.0	4.0–6.0	....	1.0 max.	0.30 max.	0.05 max.	....
Yellow brass	B135	Alloy No. 3	P, FF	65.0–68.0	....	0.30–0.80	Remainder	....	....	0.07 max.	....	....
Silicon bronze	...	....	P, F, FF	Remainder	....	0.05 max.	1.50 max.[b]	2.75–3.50	....	0.25 max.	....	Mn 1.50 max.
Silicon bronze	B198	12A	CV, CF	Remainder[c]	1.0 max.	0.5 max.	5.0 max.	1.0–5.0	....	2.5 max.	....	Al 1.50 max., Mn 1.50 max.
70–30 Copper-nickel	B111	....	P, FF	Remainder	1.50 max.	0.05 max.	1.0 max.	....	29.0–33.0	0.6 max.	....	Mn. 1.50 max.
70–30 Copper-nickel	...	....	CV, CF	Remainder	....	0.03 max.	1.0 max.	0.70 max.	28.0–32.0	0.30–0.50	....	Mn 1.50 max., Al 0.50 max., Ti 0.25 max., C 0.15 max.

[a] P, pipe; F, forged fittings; FF, wrought fittings; FV, forged valves; CV, cast valves; CF, cast fittings.
[b] Manganese or zinc may be used. Total of impurities shall be 0.50% max.
[c] Copper plus named elements = 99.5% min.

Table 5b—Welding and Service Conditions for Copper and Copper Alloy Piping

Name or Standard Type Number	ASTM Spec. No.	General Use	Service Temperature Limits, °F.	Welding			Preheat
				Process[a]	Filler Metal[a]	Flux	
Deoxidized copper	B42	General, corrosion resistance and sub-zero service	—320 to 400	A, B, C, F	1, 2, 5, 6, 7, 8, 9	Flux is required with all metals and all processes except when the process employed is either the inert gas metal-arc or shielded metal-arc.	Six inch and larger pipes usually require adding heat by means of a torch diametrically opposite where molten metal is being deposited.
Deoxidized copper	B75	General, corrosion resistance and sub-zero service	—320 to 400	A, B, C, F	1, 2, 5, 6, 7, 8, 9		
Deoxidized copper (arsenical)	B75	General, corrosion resistance and sub-zero service	—320 to 400	A, B, C, F	1, 2, 5, 6, 7, 8, 9		
Red brass	B43	General, corrosion resistance and sub-zero service	—320 to 500	A, B, C, F	1, 2, 5, 6, 7, 8, 9		
Steam or valve bronze	B61	General, corrosion resistance and sub-zero service	—320 to 550	A, F	5, 6, 7, 8, 9		
Composition brass	B62	General, corrosion resistance and sub-zero service	—320 to 500	A, F	5, 6, 7, 8, 9		
Yellow brass	B135	General and mild corrosion service	—20 to 500	A, B, C, F	5, 7, 8, 9		
Silicon bronze	....	Specific corrosion resistance and sub-zero service	—320 to 350[b]	A, B, C, D, E	3, 5		Silicon bronze and wrought 70–30 copper-nickel generally do not need preheat. Cast 70–30 copper-nickel should be preheated and, if possible, furnace cooled.
Silicon bronze	B198	Specific corrosion resistance and sub-zero service	—320 to 350[b]	A	5		
70-30 Copper-nickel	B111	Sea water and other corrosion resistance	—320 to 700	A, B, D	5, 10		
70-30 Copper-nickel	....	Sea water and other corrosion resistance	—320 to 700	A	5		

[a] The processes listed are those most commonly utilized in manual welding of piping assemblies. The legend, indicating the process and filler metals usually employed, is as follows:

Process: A = Oxy-acetylene brazing B = Oxy-acetylene welding; C = Inert-gas metal-arc welding; D = Shielded metal-arc welding; E = Carbon-arc welding; F = Soft soldering.

Filler Metal: 1 = Deoxidized copper; 2 = Phosphor bronze; 3 = Silicon bronze; 4 = Aluminum bronze; 5 = Silver brazing alloy; 6 = Brazing spelter; 7 = Soft solder; 8 = Naval brass; 9 = Manganese bronze; 10 = 70–30 copper-nickel.

[b] There is doubt concerning the suitability of this material when exposed to certain media and/or high temperatures, particularly steam above 212°F. The user should satisfy himself that it is satisfactory for the service for which it is to be used.

Table 6a—Properties of Nickel and Nickel Alloy Piping Materials

Name or Standard Type Number	ASTM Specifications No.	Grade	Form[a]	Chemical Composition, % Nickel	Copper	Chromium	Iron	Manganese	Carbon	Silicon	Sulfur	Aluminum
Nickel	B161	....	P, FF	99.0 min.	0.25 max.	....	0.50 max.	0.35 max.	0.20 max.	0.50 max.	0.02 max.	....
Nickel	....	....	CV, CF	96.0–98.0	0.30 max.	....	0.25 max.	0.50 max.	0.15–0.50	1.0–1.5	0.015 max.	....
Nickel-copper (Monel)	B165	....	P, FF	63.0–70.0	Remainder	....	2.50 max.	2.00 max.	0.30 max.	0.50 max.	0.02 max.	0.50 max.
Nickel-copper (Monel)	....	....	CV, CF	60.0 min.	23.0 min.	....	3.5 max.	3.5 max.	C + Si, 2.0 max.	....	....	0.50 max.
Nickel-chrome-iron (Inconel)	B167	....	P, FF	75.0 min.	0.50 max.	12.0–15.0	9.00 max.	1.00 max.	0.15 max.	0.50 max.	0.02 max.	....
Nickel-chrome-iron (Inconel)	....	....	CV, CF	78.0–80.0	0.25 max.	12.0–14.0	6.0–8.0	0.25 max.	0.25 max.	2.0 max.	0.01 max.	....

[a] P, pipe; F, forged fittings; FF, wrought fittings; FV, forged valves; CV, cast valves; CF, cast fittings.

Table 6b—Welding and Service Conditions for Nickel and Nickel Alloy Piping

Name of Standard Type Number	ASTM Spec. No.	General Use	Service Temperature Limits, °F.	Welding Process[a]	Welding Filler Metal[a]	Welding Flux
Nickel	B161	Corrosion resistance and sanitary service	—320 to 500	A, B, C, D	1, 2, 7	D
Nickel	....	Corrosion resistance and sanitary service	—320 to 500	D	7	D
Nickel-copper	B165	Corrosion resistance and sanitary service	—320 to 700	A, B, C, D	3, 4, 7	A and D
Nickel-copper[b]	....	Corrosion resistance and sanitary service	—320 to 700	D	7	D
Nickel-chrome-iron	B167	Corrosion resistance and high temperature service	—320 to 1600	A, B, C, D	5, 6, 7	A and D
Nickel-chrome-iron	....	Corrosion resistance and high temperature service	—320 to 1600	A, B, C, D	5, 6, 7	A and D

[a] The processes listed are those commonly utilized in manual welding of piping assemblies. The legend, indicating the process and filler metals usually employed, is as follows:

Process: A = Oxy-acetylene welding; B = Inert-gas metal-arc welding; C = Shielded metal-arc welding; D = Torch (silver) brazing.

Filler Metal: 1 = 41 Nickel (welding rod); 2 = 131 Nickel (electrode); 3 = 40 monel (welding rod); 4 = 130x Monel (electrode); 5 = 42 Inconel (welding rod); 6 = 132 Inconel (electrode); 7 = Silver brazing alloy.

[b] Cast Monel should be preheated and, if possible, furnace cooled.

Table 7a—Properties of Aluminum and Aluminum-Alloy Piping Materials

Name or Standard Type Number	ASTM Specifications No.	Grade	Form[a]	Chemical Composition, % Aluminum	Silicon	Magnesium	Copper	Iron	Manganese	Zinc	Titanium	Chromium	Other Elements Each	Other Elements Total
43	B26, B108	S1	CV, CF	Remainder	4.5–6.0	0.05 max.	0.1 max.	0.8 max.	0.3 max.	0.3 max.	0.2 max.	....	0.05	....
B214	B26, B108	GS1	CV, CF	Remainder	1.4–2.2	3.5–4.5	0.3 max.[b]	0.8 max[b]	0.8 max.	0.3 max.	0.2 max.	0.2 max.	0.05	....
2S[c]	B209	A2	P, FF	99.0 min.	[d]	....	0.2 max.	[d]	0.1 max.	0.1 max.	....	....	0.05	0.15
3S[c]	B210	M1	P, FF	Remainder	0.60 max.	....	0.20 max.	0.70 max.	1.0–1.5	0.10 max.	....	....	0.05	0.15
61S[c]	B210	GS21	P,FF, F	Remainder	0.4–0.8	0.8–1.2	0.15–0.40	0.70 max.	0.15 max.	0.20 max.	0.15 max.	0.15–0.35	0.05	0.15
63S[c]	B221	GS21	P, FF	Remainder	0.2–0.6	0.45–0.85	0.1 max.	0.35 max.	0.10 max.	0.10 max.	0.10 max.	0.10 max.	0.05	0.15
53S[e]	B221	GS22	F, P	Remainder	45–60% of Mg.	1.1–1.4	0.1 max.	0.35 max.	....	0.15 max.	0.15 max.	0.15–0.35	0.05	0.15

[a] P, pipe; F, forged fittings; FF, wrought fittings; FV, forged valves; CV, cast valves; CF, cast fittings.
[b] If copper plus iron exceeds 0.5%, a manganese content of at least 0.3% is desirable.
[c] ASTM Specification B209 applies only to sheet and plate; however, pipe of these composition limits is also commercially available. Specification B210 applies only to drawn tubing; however, composition limits are correct for pipe.
[d] The permissible amount of iron and silicon is 1.0%.
[e] No applicable ASTM specification exists. Composition limits given are those commercially available.

Table 7b—Welding and Service Conditions for Aluminum and Aluminum-Alloy Piping

Name or Standard Type Number	ASTM Spec. No.	General Use	Service[a] Temperature Limits, °F.	Welding Process[b]	Welding Filler Metal[b]	Welding Flux	Welding Preheat
43	B26	L. P. steam, water, air and resistance to corrosion	32 to 250	D	2, 3		
B214	B26	L. P. steam, water, air and resistance to corrosion	32 to 250	D	2, 3	Flux is required	Six inch and
2S	B209	L. P. steam, water, air and resistance to corrosion	—320 to 250	A, B, C, D	1, 2, 3	with all proc-	larger pipe
3S	B210	L. P. steam, water, air and resistance to corrosion	—320 to 250	A, B, C, D	1, 2, 3	esses except	may require
61S	B210	L. P. steam, water, air and resistance to corrosion	—320 to 250	A, B, C, D	2, 3	inert-gas	adding heat
63S	B221	L. P. steam, water, air and resistance to corrosion	—320 to 250	A, B, C, D	2, 3	metal-arc.	by means
53S	B221	L. P. steam, water, air and resistance to corrosion	—320 to 250	A, B, C, D	2, 3		of a torch.

[a] For many applications, service temperatures higher than 250°F. are satisfactory, but cognizance must be taken of the lower mechanical properties existing at these elevated temperatures. On the other hand, certain materials which can successfully be handled at room temperature or below should not be handled at elevated temperatures.
[b] The processes listed are those most commonly used in manually welding piping components. The legend, indicating the process and the filler metal usually employed, is as follows:
Process: A = Inert-gas metal-arc welding; B = Oxy-hydrogen welding; C = Oxy-acetylene welding; D = Oxy-hydrogen brazing.
Filler Metal: 1 = Type 2S aluminum; 2 = Type 43S aluminum alloy; 3 = Aluminum brazing alloy.

Table 8a—Properties of Lead and Lead Alloy Piping Materials

Name or Standard Type Number	ASTM Specifications No.	Grade	Form[a]	Chemical Composition, % Lead	Silver	Copper	Arsenic+ Antimony+ Tin	Zinc	Iron	Bismuth	Others
		A		99.85 min.	0.002 max.	0.0025 max.	0.015 max.	0.002 max.	0.002 max.	0.15 max.	....
Common lead[b]	B29	B	P, FF, CV	99.73 min.	0.002 max.	0.0025 max.	0.015 max.	0.002 max.	0.002 max.	0.25 max.	....
Chemical lead[b]	B29	....	P, FF, CV	99.90 min.	0.002-0.020	0.08 max.	0.002 max.	0.001 max.	0.002 max.	0.005 max.	....
Pure Commercial Lead[b]	B29	Corroding Lead	P, FF, CV	99.94 min.	0.0015 max.	0.0015 max.	....	0.0015 max.	0.002 max.	0.05 max.	Arsenic,[c] 0.0015 max.
Antimonial lead[d]	...	....	P, FF, CV	94.0	....	....	6.0	....	....	....	....
Tellurium lead[d]	...	....	P, FF, CV	99.88	....	0.06	....	....	....	....	Tellurium, 0.045

[a] P, pipe; F, forged fittings; FF, wrought fittings; FV, forged valves; CV, cast valves; CF, cast fittings.
[b] Common Leads A and B—Designations that are used to describe fully refined desilverized lead.
Chemical Lead—Used for many years to describe undesilverized lead produced from Southeastern Missouri ore.
Corroding Lead—Used for many years to describe lead which has been refined to a high degree of purity.
[c] In addition, the following maximum percentages are specified for corroding lead: Silver and copper 0.0025; antimony + tin 0.0095.
[d] Nominal compositions only are given as these metals have not been standardized.

Table 8b—Welding and Service Conditions for Lead and Lead Alloy Piping

Name or Standard Type Number	ASTM Spec. No.	General Use	Service Temperature Limits,[a] °F.	Welding Process	Filler Metal	Flux	Preheat
	B29A						
Common lead	B29A,B	Corrosion resistance	0 to 150	oxy-hydrogen	Common lead	None	None
Chemical lead	B29	Corrosion resistance	0 to 300	oxy-hydrogen	Chemical lead	None	None
Pure commercial lead	B29	Corrosion resistance	0 to 150	oxy-hydrogen	Pure commercial lead	None	None
Antimonial lead	....	Corrosion resistance	0 to 284	oxy-hydrogen	Antimonial lead	None	None
Tellurium lead	....	Corrosion resistance	0 to 300	oxy-hydrogen	Tellurium lead	None	None

[a] Lead exhibits marked creep characteristics even at room temperature. At elevated temperatures low working stresses and special supports must be employed.

General Usage, Service Temperature Limitations and Welding Requirements

Tables 5*b* to 8*b* parallel Tables 5*a* to 8*a* and summarize the service conditions to which the various materials listed are generally applied, the temperature ranges over which they are normally used and the filler metals commonly used with each base material.

Allowable Working Stresses and Pressures

Allowable working stresses for copper and brass pipe and tubing and (by inference) wrought welding fittings made from these materials are published in Section VIII of the ASME *Boiler Code*, and also in the ASA *Code for Pressure Piping* in each major subdivision thereof. Section VIII also establishes allowable working stresses at various temperatures for copper-nickel, nickel and nickel alloy pipe as well as copper-silicon shapes and Types 2S and 3S aluminum sheet. The allowable working stresses at room temperature also can be used at lower temperatures. Practically all of the nonferrous metals and alloys retain their toughness, hence their ability to resist shock and impact, down to temperatures at least as low as —320°F.; thus, they are frequently employed for sub-zero services in preference to all but the nickel and austenitic stainless steel alloys. The allowable working stress for materials not covered by the codes should be either one-fourth of their ultimate strength at the operating temperatures, or the stress required to produce 1% creep in 100,000 hr. at the operating temperature, whichever is lower, unless the piping falls under the jurisdiction of Section I of the ASME *Boiler Code* or the Power or District Heating Sections of the *Piping Code*. In these cases, the allowable stress is one-fifth the ultimate strength or 80% of the stress producing 1% creep in 100,000 hr. at the operating temperature. For Boiler Code piping it is necessary to obtain the actual allowable stress from the ASME Boiler Code Committee. For piping under the jurisdiction of the *Code for Pressure Piping*, it is recommended that application be made to the Piping Code Committee for the allowable working stress, particularly for service temperatures above 200°F. This is because most nonferrous metals, except nickel alloys, begin to exhibit appreciable creep at about 200°F.

Allowable pressure ratings for nonferrous components other than pipe and wrought butt-welding fittings must be obtained from the manufacturers since there are no American Standards covering them.

Backing (Welding) Rings

The use of backing rings is often impossible in piping services where corrosion, fluid contamination or sanitary requirements dictate the use of nonferrous materials. When the service is such that backing rings will not produce harmful conditions, for example, where the nonferrous material is used only because of its superior low-temperature properties, such rings will aid materially in economically producing sound welds. When backing rings are employed, they should be made of material having substantially the same chemical composition as the pipe. The only exception to this rule is found in those cases where it is possible to employ rings of high melting point material which are removed from the joint after its completion.

DESIGN

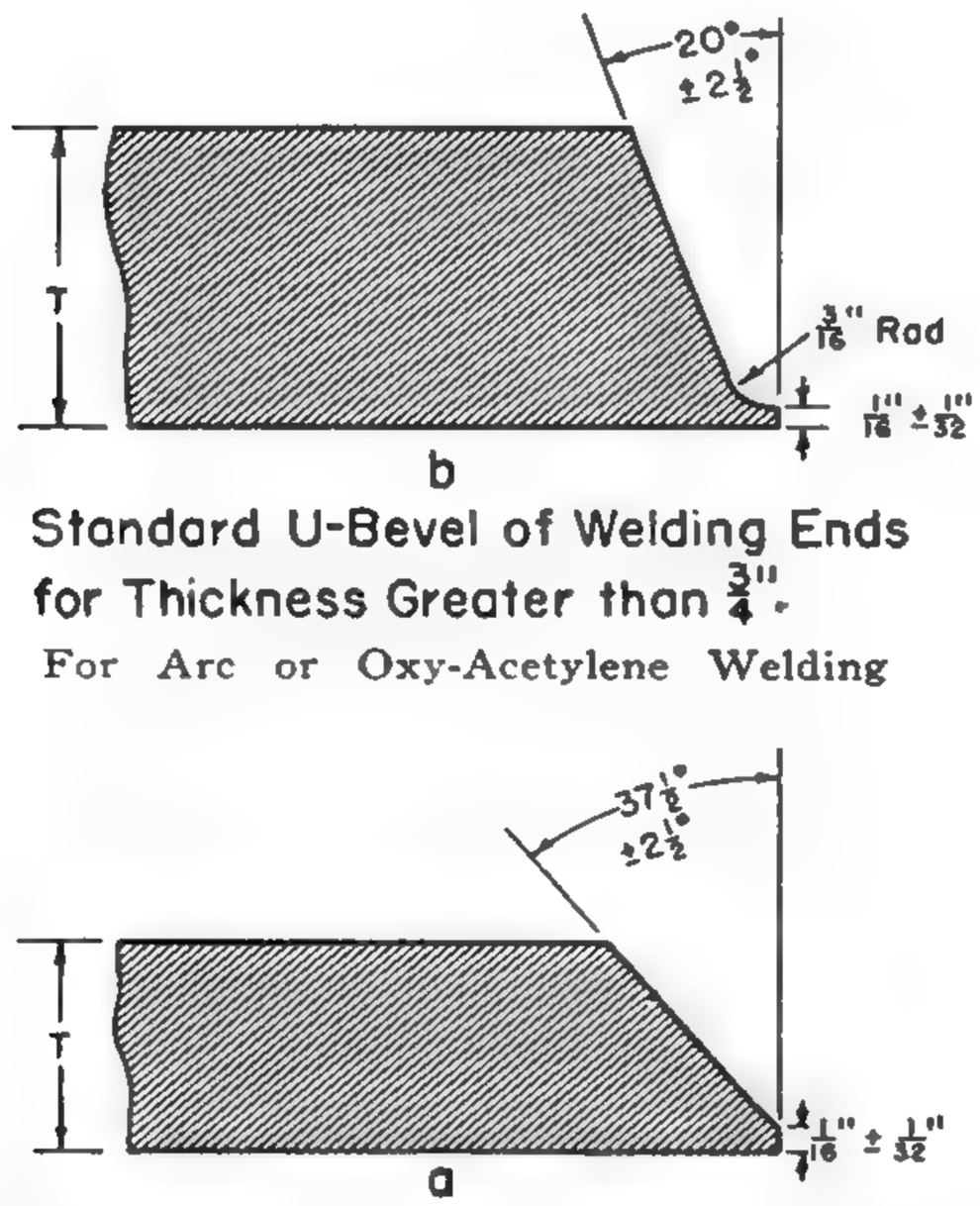
Groove Welds

Simple Butt Joints.—The most common type of joint employed in the fabrication of welded pipe systems is the circumferential butt joint. It is the most satisfactory from the standpoint of stress distribution. Its general field of application is pipe to pipe, pipe to flanges, pipe to valve and pipe to fitting joints. Butt joints may be used for all sizes, but fillet-welded joints can often be used to advantage for pipe 3 in. and smaller in diameter.

While there are no universally accepted welding grooves, the bevels shown in Fig. 1 are now considered for all practical purposes as standard for industrial piping. These bevels appear in the American Standard for *Steel Pipe Flanges and Flanged Fittings*, ASA B16e, and in the American Standard for *Butt Welding Fittings*, ASA B16.9, as recommended practice and much of the piping fabricated since publication of ASA B16e has been furnished with one or the other of them. For oxy-acetylene welding there is some preference for a 75- or even a

60-deg. groove angle for all pipe thicknesses, and some fabricators, particularly those using the forehand techniques, prefer a 90-deg. groove angle.

Butt Joints Between Unequal Thicknesses.—When pipes or vessels of unequal wall thickness are to be welded, care should be taken to provide a smooth taper on the edge of the thicker member. The length of the taper should be at least 4 times the offset between the pipe or vessel thicknesses, as outlined in Par. P104(d) and Par. U-72(e) of the ASME *Power Boiler Code* and *Unfired Pressure Vessel Code*, respectively. The two methods of alignment which are recommended are shown in Fig. 2.



Standard U-Bevel of Welding Ends for Thickness Greater than 3/4".

For Arc or Oxy-Acetylene Welding

Standard Straight Bevel of Welding Ends for Thickness 3/16" to 3/4" Inclusive.

Not Recommended for Oxy-Acetylene Welding

Fig. 1.—Commonly Used Edge Preparations for Pipe Welding

The wall thickness of cast steel fittings and valve bodies is normally greater than that of the pipe to which they are joined. In order to provide equal thicknesses for welding, the ASME *Power Boiler Code* permits the machining of the cylindrical ends of cast steel fittings and valve bodies to the nominal wall thickness of the adjoining pipe, provided these areas are finish-machined both inside and outside and are carefully inspected. The machined ends may be extended back in any manner provided the longitudinal section comes within the maximum slope line indicated in Fig. 2. The transition from the pipe to the fitting or valve end at the joint must be such as to avoid sharp re-entrant angles and abrupt changes in slope.

Fillet Welds

Circumferential fillet-welded joints are generally used for joining pipe to pipe, pipe to flanges, pipe to valves and pipe to socket joints in the smaller sizes—i.e., about 3 in. and under. This type of joint is particularly suited for these applications because it accomplishes in small-sized pipes, without backing rings and without restricting fluid flow, what is accomplished in large-size pipe by the use of backing rings. The fact that a backing ring appreciably reduces the internal area of small-diameter pipe precludes its general use in that field. Figure 3 illustrates three typical fillet-welded joints. Since this type of weld is subjected to shearing and bending stresses, adequate penetration of the pieces being joined is

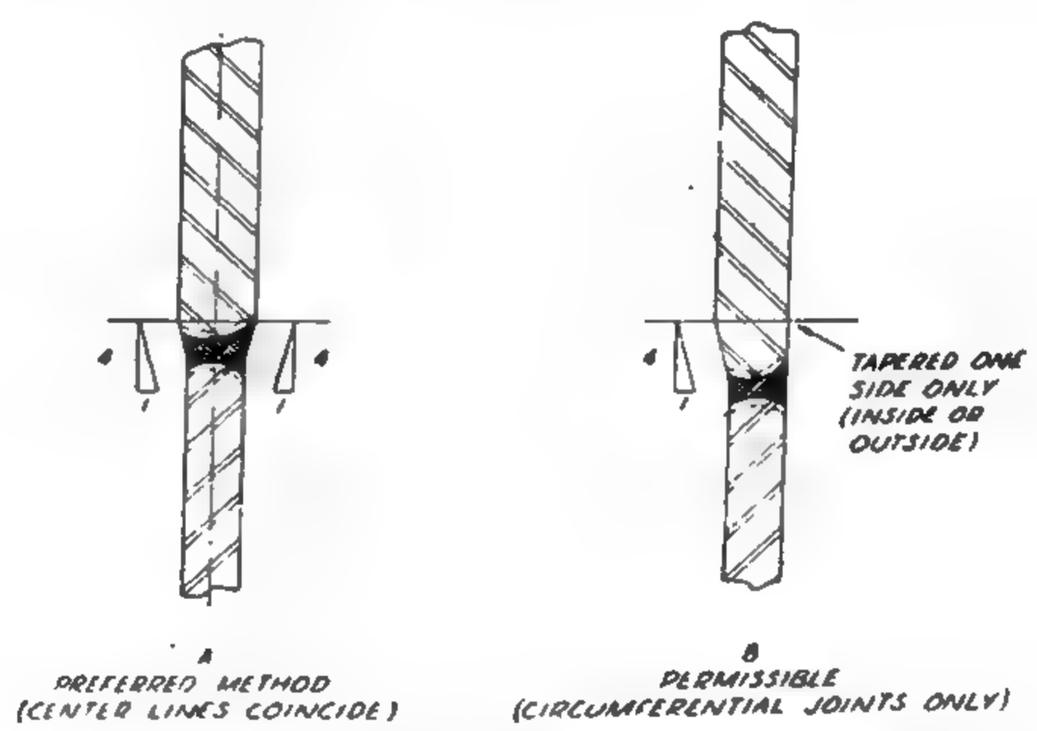


Fig. 2.—Typical Welding-End Sections for Valves and Fittings of Unequal Thicknesses

a positive requirement. This is particularly important with the socket joint since the danger of *washing down* the end of the hub may obscure, by reason of fair appearance, the lack of a full and sound fillet weld. This condition is one which

cannot be detected in the finished weld by the usual visual inspection aids.

Intersection Type Joints

Intersection joints such as medium and large size welded tees, laterals, wyes, openings in vessels, etc., are usually the most difficult to weld. In consequence, factory-made wrought steel fittings conforming to ASTM Specification A-234, *Factory-Made Wrought Carbon-Steel and Carbon-Molybdenum-Steel Welding Fittings*, are preferred for accomplishing the layout of the piping system, since they provide bursting strengths equivalent to that of pipe of the same weight or schedule, and their installation involves butt welds only. Machines for oxygen cutting and beveling header openings and branch ends are available, but not in general use. Cutting and beveling is usually done manually with an oxy-acetylene cutting torch. Figure 4 illustrates two forms of preparation for 90-deg. intersection joints. In one, the header opening is sufficient to permit insertion of the branch, and the header opening only is beveled. In the other, the header opening is equal to the inside diameter of the branch, and the branch only is beveled. The latter form permits the use of a specially shaped backing ring if desired. Unreinforced branches, as illustrated in Fig. 4, are adequate only where the pipe is to be used at pressures considerably below its full capacity, usually between 50 and 75% of the pressure which the run of the pipe can safely withstand. In order to make 90-deg. intersections equivalent in strength to the pipe from which they are fabricated, reinforcing is required. The design of such reinforcing is beyond the scope of this Chapter. Reference should be made to Par. 634(c) of the ASA *Code for Pressure Piping* or Chapter 5 of the *Standard Manual on Pipe Welding* of the Heating, Piping and Air Conditioning Contractors National Association.

The intersection of two pipes at an angle of 45 deg. or less produces a condition at the crotch of the intersection which makes it difficult, if not impossible, to secure the degree of penetration and soundness of weld deposit that is considered essential for severe service conditions. Such intersection welds should be avoided for service where the pressure exceeds approximately 125 psi. Piping should be designed, whenever it is at all

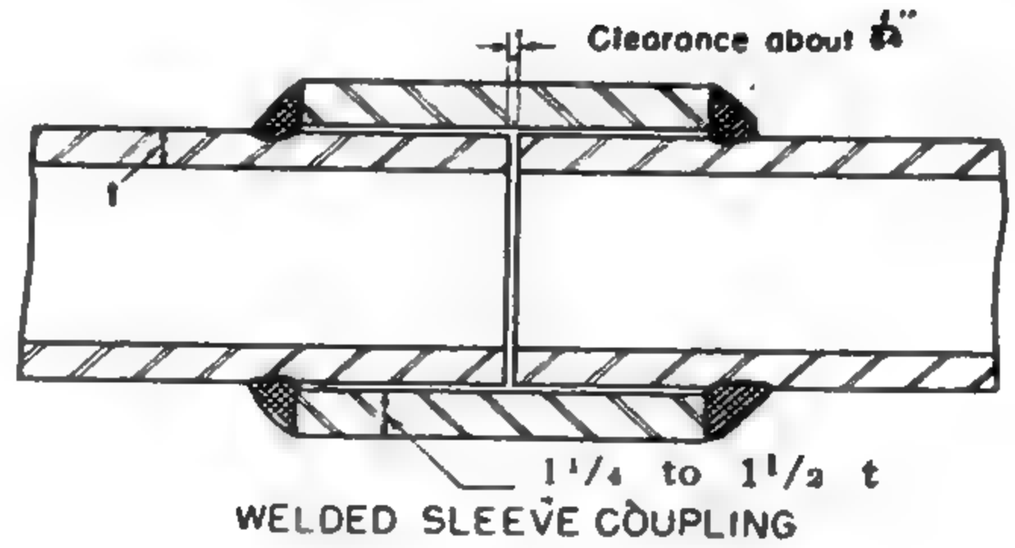
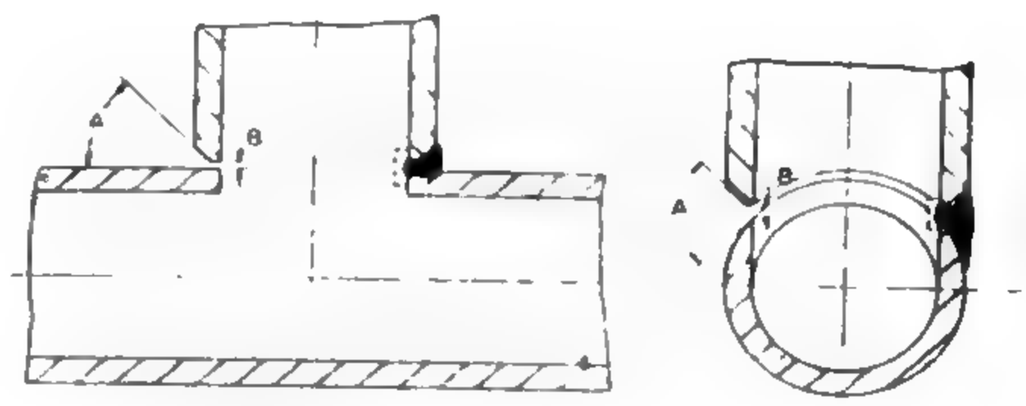


Fig. 3.—Typical Fillet-Welded Joints



Angle *A* to be not less than 45° for any wall thickness of pipe Dimension *B* to be not less than 1/16 in. nor more than 1/4 inch.

Fig. 4.—Acceptable Types of Preparation for 90-Deg. Intersection Welds

possible, so that all intersection joints regardless of angle can be made under shop conditions, where work can be positioned for welding in the flat position.

Manufacturers today have simplified the problems of the fabricator by providing factory-made welding type nozzles, welding necks and welding tees, and other types of outlets especially for welding which eliminate a great deal of the cutting, tacking and fitting previously required in this type of construction. Typical nozzle, neck and welding outlets which can be used for almost all ranges of sizes are shown in Fig. 5.

Welding Fittings

Manufacturers have kept pace with design for welding by providing a line of fittings especially for welding and available in most grades of material suitable for welding. These fittings can be obtained in many combinations of size and thickness, and combining the best characteristics for unimpaired flow conditions with ease of welding and ready procurement, they make the use of mitred construction obsolete. Some typical fittings for welding are shown in Fig. 6. Manufacturers' catalogs should be consulted for further details and dimensions.

Welding flanges are also available in either the socket, slip-on, lap-joint type for use with welding stub ends or butt-joint type. These are shown in Fig. 7. The use of slip-on and socket types is usually restricted to services not exceeding 300 psi., since the applicable ASA Standard (B16e) does not include slip-on flanges for pressure ratings above 300 psi. and does not include socket weld flanges at all. Butt-joint and lap-joint types for use with welding stub ends are not subject to such restrictions.

Backing Rings

The term *backing ring* is applied to a ring-shaped structure which is fitted to the inside surface of the pipe prior to welding. Its function is to assist the welder in securing complete penetration without burning through, to prevent spatter and slag from entering the pipe at the joint, and to prevent the formation on the inside of the joint of irregular shaped masses of metal, sometimes called *icicles* or *grapes*.

Backing rings also assist materially in securing proper alignment of the pipe ends. They are used extensively in the welding of piping for severe service conditions, where internal cleaning cannot be carried out subsequent to welding and where the elimination of spatter is essential for the protection of valves, turbine blading, gears, etc.

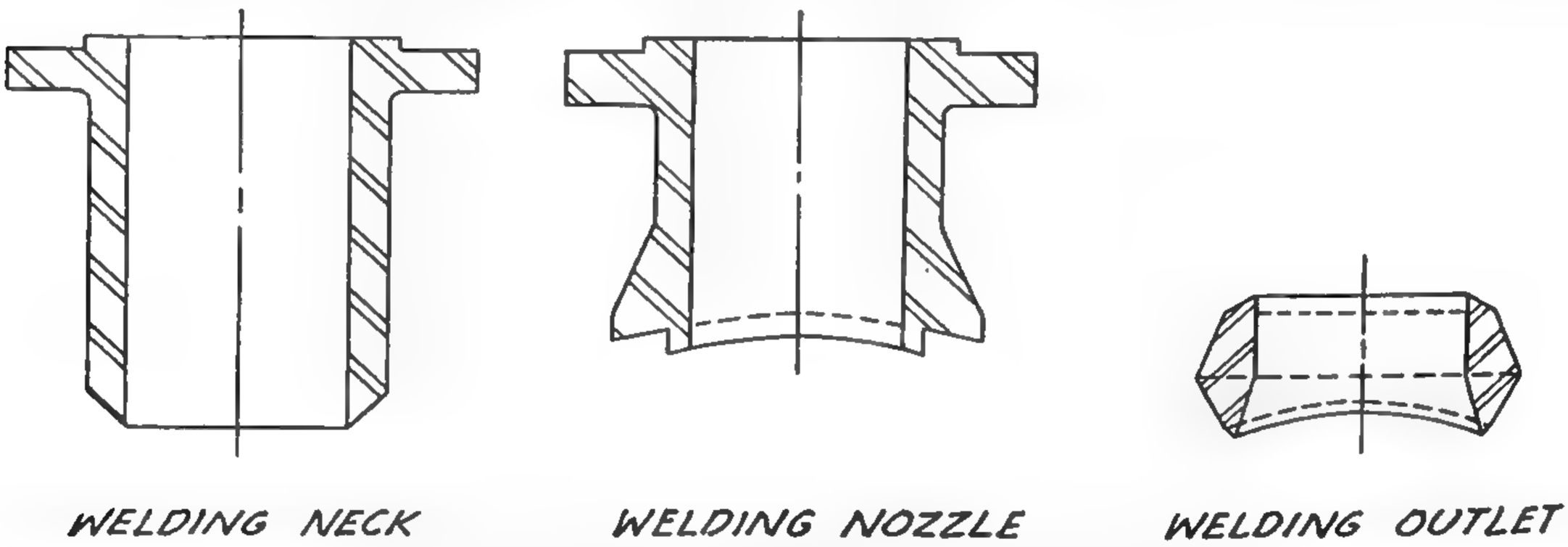


Fig. 5.—Typical Nozzle, Neck and Welding Outlets

Many different shapes of backing ring are used, as well as a special type end preparation in which a lip is formed and subsequently rolled inward, designed to serve as a substitute for a separate ring. The fact that so many designs are being used is indicative of the lack of agreement among engineers as to what constitutes an acceptable ring, and seems to justify a somewhat detailed discussion of the subject.

It is convenient to classify backing rings as two types: split or continuous. Split rings are, in general, designed to fit the inside diameter of the members to be joined without any preparation of these parts to receive the rings. The outstanding characteristic of such rings is that being split, they may be slightly contracted or expanded to fit the inside diameter snugly. Because of the variation in diameter of commercial piping, it is impossible to make such rings to dimensions

which will fit all pipes of a given size and weight without having a rather large gap when the pipe variation is at a maximum (on the large side) or without cuting the ring to make it fit when the pipe variation is at a minimum (on the small side). The usual commercial practice is to make the rings of dimensions such that the gap will be $^{2}/_{16}$ to $^{1}/_{4}$ in. for pipe of nominal dimensions. When the two pipe ends are not of the same inside diameter, split rings will fit snugly only against the smaller of the two pipes, and there will be a gap between the ring and the inside wall of the larger pipe. This condition is not considered serious in the welding of piping for moderate service conditions. However, the desire to provide a design which would insure a snug fit between ring and pipe ends, even when the pipe ends are of slightly different diameters, has led to the introduction of a second type of backing ring, commonly termed *continuous rings.*

The use of continuous rings requires that the pipe ends be specially prepared by machining, grinding, flaring and in some cases by upset forging or by building them up with weld metal. Since preparation of the pipe ends is an added expense and since the rings themselves are more expensive than the split type, their use is generally restricted to piping systems designed for the most severe service conditions. Typical joint designs using backing rings are illustrated in Fig. 8.

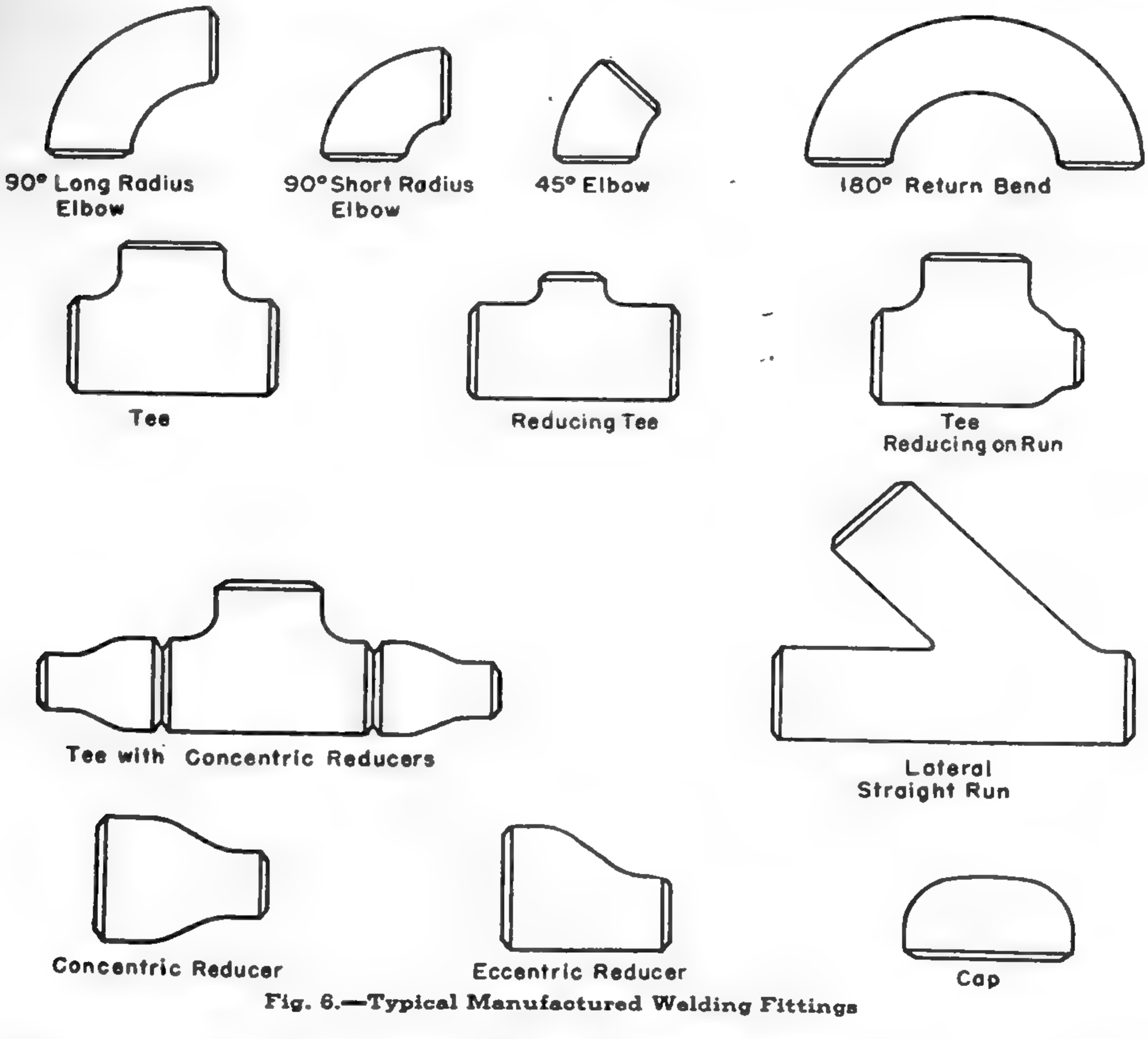


Fig. 6.—Typical Manufactured Welding Fittings

The outer surface of backing rings, namely, that which bears against the inside wall of the pipe, is provided in various forms. Split rings are provided with flat, ridged and grooved surfaces, continuous rings with flat and grooved surfaces (see Fig. 8). The flat surface was the original form and is still considered

by some as the best for arc welding. The grooved surface was found necessary for gas welding and is now considered by many as superior to the flat surface for arc welding. The ridged surface was intended to provide a means for properly spacing the pipe ends. It does that, but at the expense of making it difficult, if not impossible, to secure complete penetration, and is not now used to any great extent.

It is generally agreed that the ring thickness should be the least possible in order to minimize the pressure drop. It is recognized, also, that the required thickness is related to the root opening. For root openings of approximately $^3/_{16}$ in., which are most commonly employed,

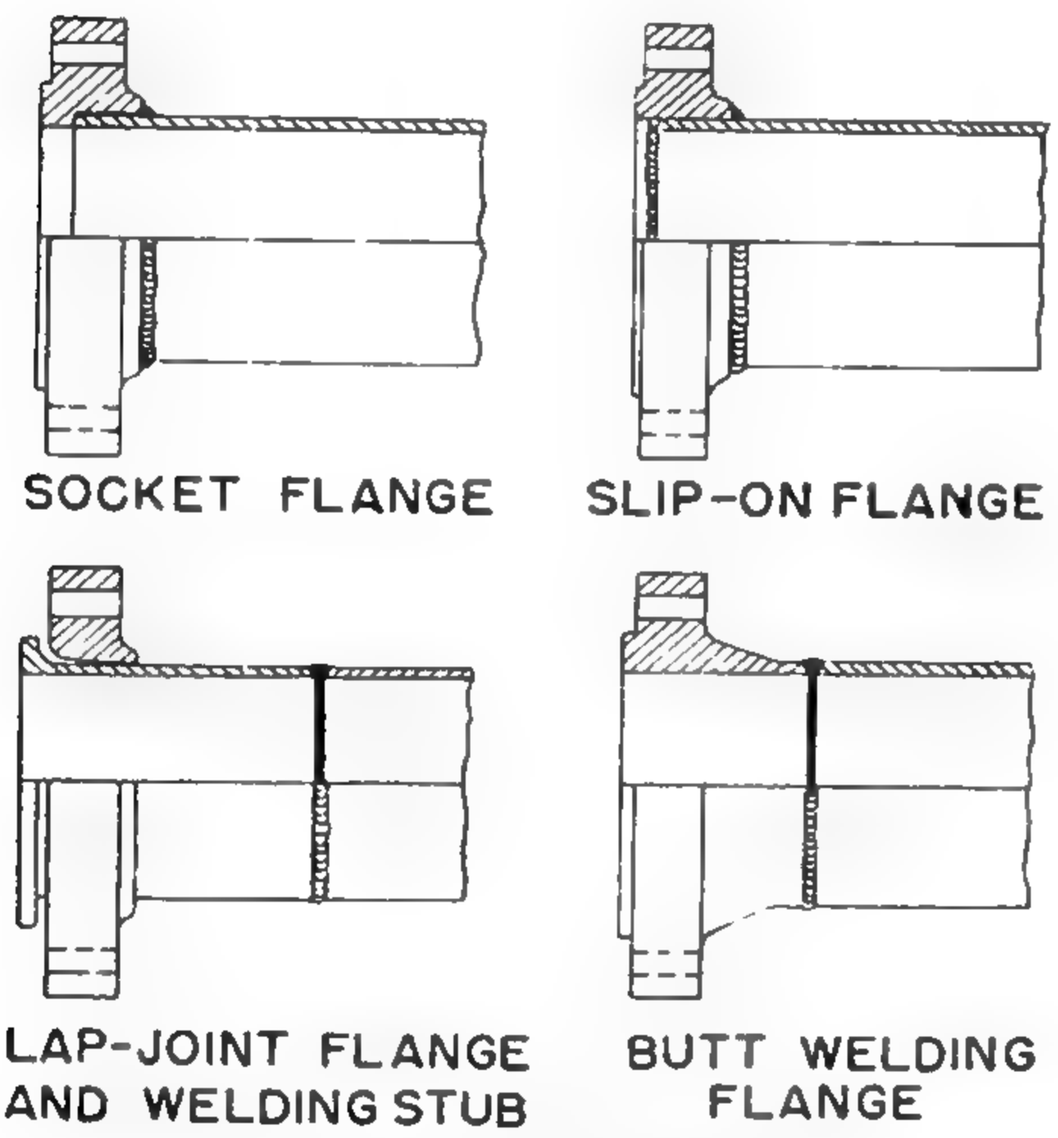


Fig. 7.—Typical Welding Flanges

experience indicates that a $^1/_8$ in. thickness is about the minimum which will permit complete fusion of the weld root without burning through the ring.

Various widths of backing rings have been used, but there seems to be general agreement now that $^3/_4$ in. is satisfactory for all except very small or very large pipe sizes. For pipe sizes exceeding 12 in., a 1 in. width is common. For pipe sizes 3 in. and smaller, a $^5/_8$ in. width is sometimes used in order to provide a better fit in welding elbows.

Correct spacing in abutting pipe ends is of paramount importance in assuring sound welds. One way of accomplishing the proper spacing is to apply clamps, but these are heavy and costly to use. The tapered continuous ring illustrated in Fig. 8 automatically, by its design, provides the desired spacing. The split ring having a ridged surface also provides the desired space but, as mentioned previously, is not now in general use. Rings with flat or grooved surfaces may readily be made to provide the desired root opening by utilizing spacing pins. Two methods of attaching such pins have been used. One method involves drilling holes around the circumference (3 holes, 120 deg. apart; seem adequate) and either inserting loose pins, which may be removed after the joint is tacked, or solidly attaching either short or long pins. If the pins are short, say, not over $^1/_{16}$ in. long, they may be welded over with assurance that they will be thoroughly fused into the first pass of weld metal. If the pins are long, they must be removed to within approximately $^1/_{16}$ in. of the ring after the joint has been tacked. The second method utilizes long pins, resistance welded to the surface of the ring. The resistance weld is controlled so as to permit breaking off the pin, at the ring surface, after the ring has been tacked in place.

Brazed Joints

Some form of the lap or shear type joint generally is necessary for brazing of connecting pipe to permit capillary attraction, which is a factor. Square-groove butt joints may be brazed but the results will be unreliable unless the ends of the pipe or tube are prepared accurately, i.e., plane and square, and the joint aligned carefully as in a jig. High strengths may be obtained with butt joints if properly prepared and brazed.

The alloys generally used in brazing exhibit their greatest strength when the least thickness of the alloy in the lap area is used; thin alloy sections also develop the highest ductility. For brazing ferrous and nonferrous piping with silver and copper-base brazing alloys, the thickness of the brazing alloy in the joint should be 0.003 to 0.006 inch. Thicknesses less than 0.003 in. will make assembly difficult, while those greater than 0.006 in. will produce joints having lowered strength. The brazing of certain aluminum alloys is similar in most respects to the brazing of other materials. However, joint clearances should be

greater because of a somewhat more sluggish flow of the brazing alloys. For aluminum a clearance of 0.005 to 0.010 in. will be found satisfactory.

The length of lap in a joint, together with the shear strength of the alloy employed, are the principal factors determining the strength of a brazed joint. The shear strength may be calculated by multiplying the width by the length of lap by the shear stress of the alloy used. An empirical method of determining the lap distance is to take it as twice the thickness of the thinner or weaker member joined. Normally, this will give adequate strength, but in cases of doubt the fundamental calculations should be employed.

Generally, such detailed determinations are unnecessary for brazed piping since commercial fittings are available in which the length of lap is predetermined at a safe value. One such fitting for brass and copper pipe is made of cast brass. A bore of correct depth to accept the pipe is provided and midway down this bore is a groove into which, at the time of manufacture, a ring of copper-silver-phosphorus brazing alloy is inserted. Since the alloy is preplaced, separate feeding of brazing alloy by hand is generally unnecessary.

Another type of brazing fitting available for pipe, is provided with a simple bore of correct diameter and depth. Brazing with this fitting requires feeding of the alloy from a hand-held wire or strip. This fitting is available in brass and malleable iron, the former for use with copper and brass pipe, the latter with steel and wrought-iron pipe. In the case of the brass fitting, the copper-silver-phosphorus or the copper-phosphorus type of brazing alloy is employed with copper and brass pipe. For malleable fittings with ferrous piping the brazing alloy should be of the silver-copper-cadmium-zinc type. Brass filler metal (60% Cu–40% Zn) of the type commonly employed in braze-welding may also be used with these ferrous fittings and pipe.

Cleanliness of the brazing area is an important consideration in brazing pipe joints. Therefore the pipe and fitting must be thoroughly cleaned with steel-wool, sandpaper, emery cloth or with a power-wire brush. Following the cleaning, brazing flux suitable for the brazing alloy to be employed must be applied to both the fitting and the pipe in the braze area. After assembling the cleaned and fluxed pipe and fitting, heating may be accomplished with an oxy-acetylene flame or other flames that will provide the necessary heat and temperature for effecting the melting and flowing of the brazing alloy. Chapter 22 contains more detailed information on brazing.

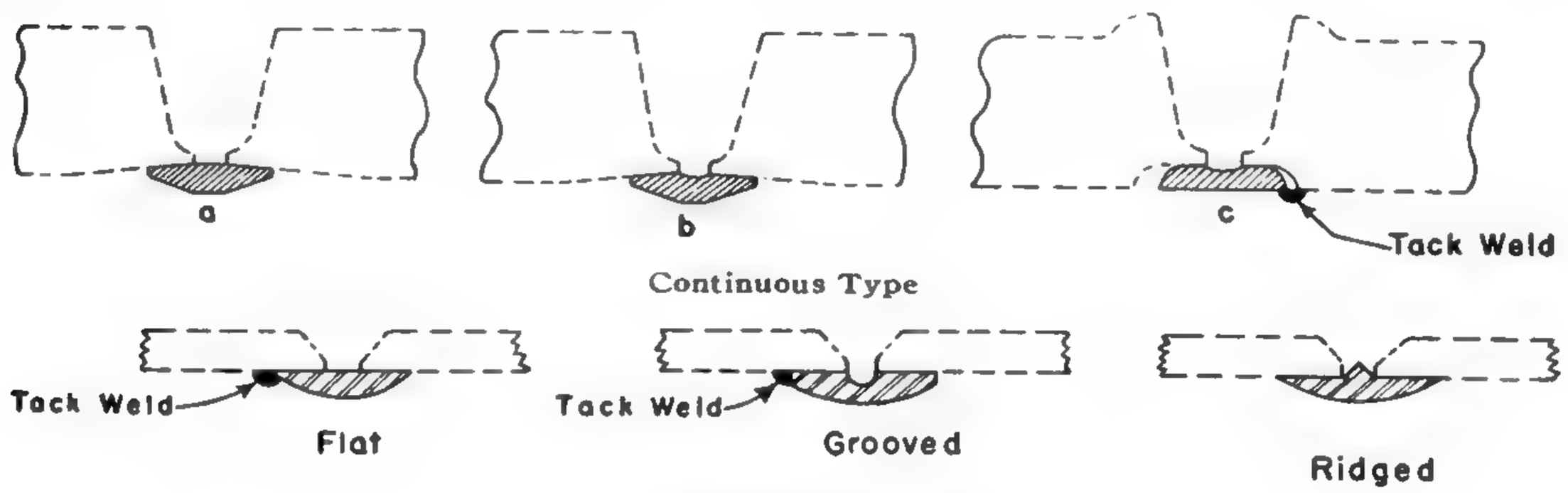


Fig. 8.—Typical Backing Rings

Soft Soldered Joints

Soft solder is generally an alloy of lead and tin in various proportions, depending upon the type of soldering to be performed. Other metals (e.g., silver, cadmium, etc.) may be added for specific properties. Generally speaking, the standard 50–50 solder (50% Pb — 50% Sn) is used in making soldered joints, while the higher lead alloys are used for wiped joints.

Solder is characterized by intrinsically low strength as compared with welding and brazing filler metals. As a result,

soldered butt joints are rarely used and instead the lap or shear type joint is employed. As in the case of brazing, the thinner the cross-section of solder (within practical limits) the stronger the joint. Best current practice requires that joint clearances be of the order of 0.003 to 0.006 inch. The strength of joints, in terms of base metal strength, may be calculated using the shear strength of the particular solder employed.

Soldered connections in piping are used principally on brass and copper tubing. For this service a number of fittings are available (ells, tees, etc.), some wrought copper, others cast brass, but all specifically designed for soldering. The bores of these fittings provide the proper clearance for the tubing. If annealed tubing is used and it is out of shape or size, tools are available for reshaping and resizing it.

Another application of soldering to piping is for sealing threaded joints. In this case the solder is not expected to provide any strength but merely seals the threads to ensure against leakage. The threaded joint is made up in the usual manner and solder is applied at the juncture of the pipe and fitting in the form of a fillet. Chapter 23 contains further information on soft soldering.

Lead Welded Joints

The design of joints for welding (sometimes erroneously called lead burning) lead pipe joints is essentially the same as for other forms of welding. For thicknesses less than $^3/_{16}$ in. the square-groove butt joint is employed. Thicknesses greater than $^3/_{16}$ in. require beveling to an angle of 10 to 15 deg. to give a groove angle of 20 to 30 degrees. The pipe ends are first cut square and then beveled. A typical single-vee groove butt joint for lead pipe is shown in Fig. 9.

Other types of joints are sometimes employed under special conditions. One of these is the cup joint, illustrated in Fig. 10, which is similar to a *bell and spigot* joint as used in cast iron. Still another special type joint is the welded flange joint pictured in Fig. 11. In this joint a fillet weld is employed. Since lead is a soft metal these joints may be prepared readily with simple hand tools.

Occasionally situations will be encountered where the under side of the pipe joint will be inaccessible for welding. In metals other than lead such conditions should be avoided by careful field planning. In welding lead pipe, however, the solution is relatively simple by use of a split joint as shown in Fig. 12. Such manipulation is possible with lead because of its extreme ductility.

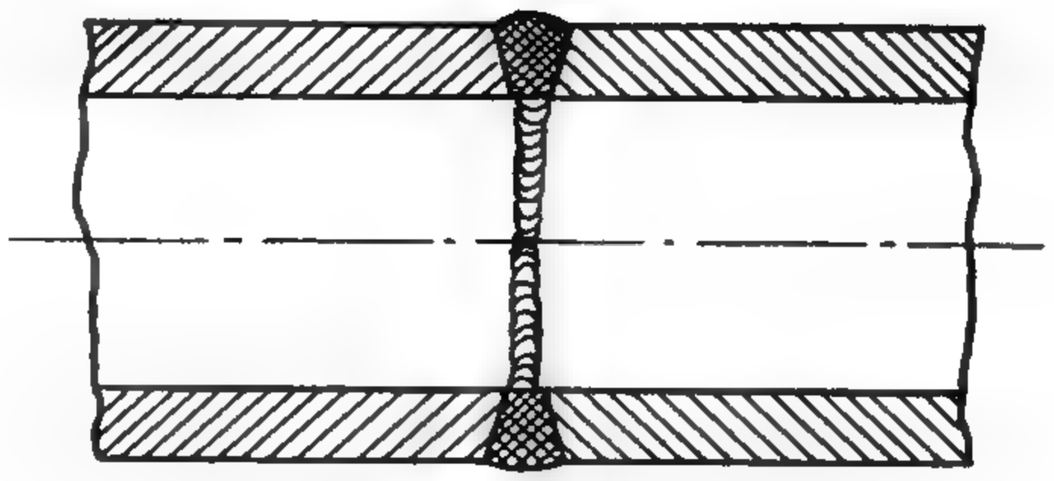


Fig. 9.—Butt Joint for Lead Pipe

Cleaning the joint before welding lead is very important. The edges and about $^1/_2$ in. on each side should be scraped with a scraper and welding should proceed within a short time after the cleaning. Chapter 36 contains further information on the welding of lead.

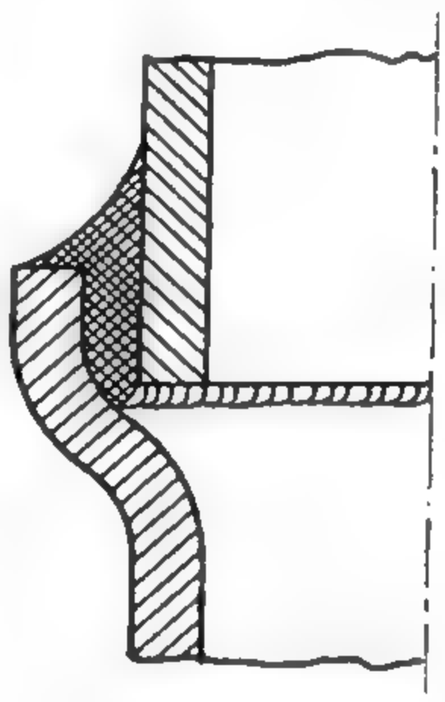


Fig. 10.—Cup Joint for Lead Pipe

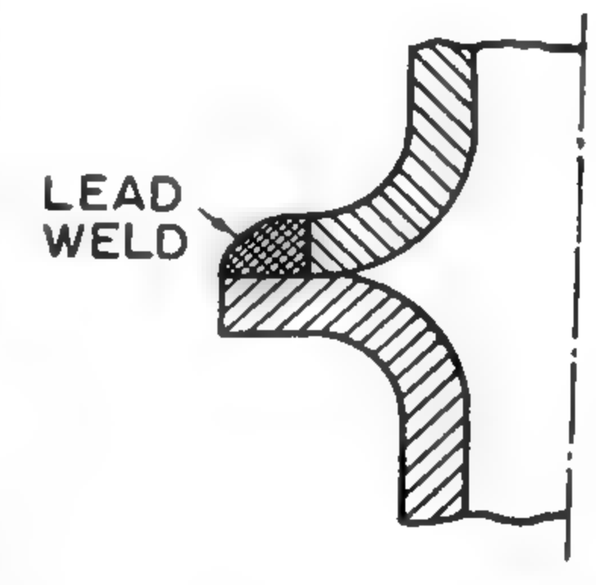


Fig. 11.—Flange Joint for Lead Pipe

Joints Between Dissimilar Metals

The joining of dissimilar metals by any of the welding processes is dependent upon the relative melting points of the metals to be joined. Thus if the melting points are close (some authorities state within 50°F.), it is generally possible to

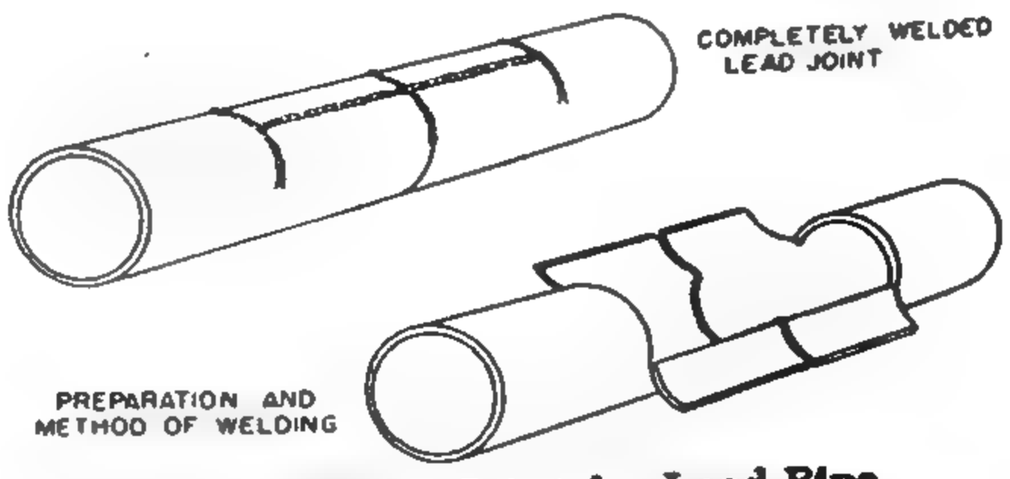


Fig. 12.—Split Joint for Lead Pipe

use either arc or gas welding, using a filler metal matching one of the base metals. If, however, there is a wide difference in melting points, then it becomes necessary to resort to brazing, braze-welding or soldering. There is the further qualification that each of the metals involved in the joint must individually be capable of being welded, brazed or soldered.

The design of joints for welding dissimilar metals is exactly the same as that for welding similar metals. Groove and fillet welds of the standard proportions are employed. The differences in coefficients of expansion, thermal conductivity, etc., influence the welding techniques and procedure, not the joint design. Actually, there are very few dissimilar metals which may be welded. Stainless steels are sometimes welded to mild or low-alloy steels, generally using stainless steel filler metal. Similarly, nickel and some nickel alloys may be welded to mild and stainless steels as discussed in Chapter 35.

Brazing with silver-copper-cadmium-zinc alloys offers the best approach to joining dissimilar metals where the presence of this alloy is acceptable from the point of view of service requirements. It should be pointed out that copper-phosphorus and copper-silver-phosphorus brazing filler metals are suitable only for copper and copper base alloys, hence they should be used with care on dissimilar metals; they cannot be used on ferrous metals or nickel or its alloys. The standard joints employed in brazing similar metals apply equally well to dissimilar metals.

Soft soldering provides a means of connecting metals of widely differing melting points, particularly where one of the metals melts below the temperatures necessary for brazing. Soldering is also helpful in those situations where it is necessary to avoid the high temperatures of welding and brazing. Joint designs for soldering dissimilar metals follow the principles and standards established for soft soldering similar metals.

WORKMANSHIP

General Considerations

The facilities available in a permanent shop planned for pipe welding offer an efficient means for securing workmanship of the quality essential in industrial piping. These facilities include power-driven machines for cutting and beveling operations, accurate layout equipment, power-driven welding positioners, modern welding equipment for manual, semi-automatic, and automatic processes, adequate apparatus for destructive and non-destructive testing, heat treating equipment and efficient material handling devices. Inspection and testing operations are done under close supervision, and control of weld quality is maintained through laboratory research and testing.

While the usual shop erected in the field is seldom as fully equipped as a permanent shop, equally high quality workmanship can be obtained if care is exercised in the design of the shop, the selection of equipment, and in the selection and training of the operating, supervisory and inspection personnel. An important factor in developing uniform, high quality workmanship is the care that is exercised in the use of facilities and a knowledge of their limitations, rather than whether such facilities are of a permanent or temporary nature.

Assembly and Preparation for Welding

The following has been written for the purpose of outlining in a general way the practices considered requisite by responsible piping contractors and piping fabricators in their daily operations to develop workmanship in pipe welding to a level of quality that will assure acceptance under any specifications.

Joint Preparation.—The end preparation of parts to be welded should be done so as to conform as nearly as possible to the joint design set up in the procedure specification. Cutting should be done, as far as possible, with some form of machine tool or mechanically-guided oxygen torch. The latter method is limited, of course, to metals which can be so cut and are not adversely affected by the heat involved.

Where continuous-type backing rings are to be used, the required taper or counterbore of the pipe ends should conform to a standard gage. Solid backing rings, machined and tool marked for proper spacing in the joint, may be used for this purpose, one for each size and pipe thickness used in the specific construction. This practice will produce uniform ends and allow the interchange of any backing rings conforming to the gage.

All welding faces and adjoining surfaces for a distance of at least 1/4 in. from the edge of the welding groove, or from the toe of the fillet in the case of socket-welded or fillet-welded joints, should be thoroughly cleaned of rust, scale, paint, oil or grease. Oxygen-cut surfaces should be ground reasonably smooth to remove all traces of scale and any irregularities incident to cutting. Depending on the metal being welded, chemical treatment may be deemed necessary for thorough cleaning of parts and to avoid contamination during the welding.

Layout and Assembly.—Layout and assembly involves the fitting together of the various component parts comprising a subassembly, or a complete piping system, as the case may be, preparatory to welding. In these operations, dimensional allowances should be made for shrinkage during welding, and the parts to be joined should be carefully spaced, aligned and tack-welded together so that the entire assembly will conform to the required dimensions within reasonable tolerances, after welding is completed.

In making up subassemblies the usual procedure is to set up the largest component, either on adjustable trestles or on a level top table, with its longitudinal axis in a horizontal plane. The longitudinal axis and one end of the member are then used as base lines to which the locating dimensions and setting of the smaller parts can be referred, using a rule, steel tape, hand level, squares, straight edge or bevel protractor as required.

In the layout and assembly of complete piping systems in place, the same general procedure applies; first, the largest horizontal components are erected, and second, these members are used as reference points for fitting and assembling of the smaller components. In such systems, the components, whether they be pipe, valves, fittings or prefabricated assemblies, must be carefully aligned with respect to other structures, equipment and each other. In cases where no thermal expansion, contraction or other movement is involved, the aligning operations present no particular difficulty. Where such movements are a consideration, care must be exercised in both the placement and alignment to make sure that the system, after it is welded and subjected to service conditions, will position itself in a manner consistent with the design.

In assembling butt-type joints, the use of neatly fitting backing rings facilitates spacing and alignment. Where backing rings are not used the ends of the components to be welded should be carefully aligned and spaced preparatory to tacking, using some convenient spacing gage. Intersecting joints should be carefully laid out, using templates, standard layout curves or jigs. After the parts of the joint have been accurately cut and before they are beveled, it is advisable to make a trial fitting of the joint. This will permit a visual gaging to be made of the corrections that may have to be made for root spacing and alignment, etc., and will reveal any irregularities in the cutting of the parts that may require attention.

If the parts to be welded can be handled manually, the alignment, spacing, and in many cases assembly can be done without the use of external holding devices. In setting up heavy sections the use of external clamps or other means of holding the parts in correct relationship to each other is essential, not only for maintaining alignment but to facilitate handling.

In production welding, where a number of identical assemblies are involved, the use of a setting-up fixture is of considerable advantage. The design of such fixtures will vary, but the essential requirement is to provide a means for quickly setting component parts in proper relation to each other, ready for tack welding, without requiring individual clamps for each joint.

The dimensional allowances in the layout and assembly of piping systems to compensate for shrinkage during welding are established principally by experience. While it is possible to determine shrinkage for specific cases theoretically, the application of such calculations to all cases encountered in pipe welding is impractical and perhaps of questionable accuracy when it is considered that some of the variables involved in the calculations are functions of the human element.

In the usual types of butt-welded joints in carbon steel, or low-alloy steel piping of Schedule 40 and Schedule 80 thicknesses, experience indicates that the longitudinal shrinkage in each joint will equal about one-half the root spacing. Di-

ametral shrinkage is negligible and may be disregarded for all practical purposes.

In socket-welded or fillet-welded joints, both transverse and longitudinal shrinkage are negligible and need not be considered in the layout and assembly operations.

Shrinkage in the welding of intersecting joints results principally in angular distortion of the branch pipe and bowing of the main pipe. In these cases it is virtually impossible to establish even approximate shrinkage values that would hold for all cases. The steps taken to control shrinkage are quite as important as making dimensional allowances for such shrinkage in the layout and assembly operations.

It is quite important therefore in training welders in pipe welding, to emphasize the factors affecting shrinkage so that as they become experienced in applying various welding procedures, they will recognize these factors and approximate their effect in terms of dimensional allowances during layout and assembly operations. Not the least among these factors is the initial fit-up of the joint, and the necessity for careful and accurate preparation of the parts cannot be overstressed in any training program.

The ASA *Code for Pressure Piping* prescribes minimum requirements applicable to layout and assembly operations preparatory to welding. Detailed information on these operations together with instructions on template preparation and the use of standard layout curves are contained in the *Standard Manual on Pipe Welding*.

Tacking.—After the joint is properly lined up, short tack welds are made in the joint prior to actual welding. These welds should be sufficient in number and of suitable proportion to hold the parts in place during ordinary handling. They need not be any higher than one-half the thickness of the pipe wall, nor longer than twice the thickness. They should be of a quality equal to that specified by the welding procedure. Frequently in setting up joints in steel pipe of heavy wall thickness, the need for tack welds in the joints is eliminated by the use of heavy steel bridge clamps.

Welding Operations.—The welding processes most commonly used in piping installations are the manual oxy-acetylene process and the manual shielded metal-arc process. Other processes, among which are automatic and semi-automatic submerged arc, inert-gas metal-arc and atomic hydrogen welding are used to varying extents, particularly in established shops. The fundamentals of all of these processes, together with the rules governing their qualification and the qualification of welders, are treated in detail elsewhere in this HANDBOOK. The following discussion deals with the application of the various welding processes to piping installations and bears directly on workmanship.

Manual shielded metal-arc welding may be used for nearly all ferrous and nonferrous metals used in piping systems. The equipment required for its application is comparatively simple and compact, readily portable, safe to use, and, with ordinary care, requires little maintenance. Electric power supply for the operation of either d.c. or a.c. machines is readily provided in the permanent shop, and in many cases, is available for field work. If electric power is not available the use of gasoline or Diesel-engine driven welding machines will give satisfactory service.

Joint design for metal arc welding is discussed elsewhere in this chapter. The number of passes required for welding joints in ferrous piping varies with the wall thickness of the pipe, the welding position of the pipe, the size of electrode used and the welding currents employed. In welding low-carbon and low-alloy steel pipe in the rolled or horizontal position, under generally accepted procedures, the number of passes is approximately one per $^1/_8$ in. of pipe thickness. The electrodes used in these procedures vary from $^1/_8$ to $^5/_{32}$-in. diam. for the first pass; $^5/_{32}$-in. diam. for intermediate passes; and $^3/_{16}$- or $^1/_4$-in. diam. for the top passes and reinforcement.

In welding medium-carbon and higher alloy steels in the rolled or horizontal position, the number of layers is usually increased 25 to 30% and smaller electrodes are used to lessen the heat concentration and to insure complete grain refinement of the weld metal.

With the pipe in a vertical fixed position, deposition as described above is not possible, and instead the metal is deposited in the form of a series of overlapping string beads, the number of which,

when using $^{5}/_{32}$-in. max. diam. electrodes, may be approximated roughly by allowing 25 to 30 beads per sq. in. of weld area.

The number of passes for welding joints in nonferrous piping will vary to a considerable extent because of the wide differences in fusion temperatures and heat conductivities of the metals, factors which have considerable bearing on the welding technique employed.

It is common practice to do as much welding as possible in the flat or downhand position, using suitable power-driven apparatus for continuously rotating the work at a speed consistent with the rate at which the filler metal can be properly deposited. This assures uniformity both in depositing the filler metal, and in distribution of heat, thus lessening distortion. The extent to which flat position welding can be applied is limited by the dimensions, shape and weight of the component parts to be welded, the facilities for rotating the work, the amount of handling involved, and the heat-treating requirements.

Fixed position welding requires special care in depositing successive beads or layers, as called for by the procedure, uniformly around the joint in order to avoid excessive stress concentrations or distortion due to uneven heat distribution. The assembly or piping system should be positioned so that the joints are readily accessible to the welder from all points; and when preheating or stress relieving is to be done, there should be ample space for applying and removing the heating apparatus.

There is no universally accepted or recommended direction of welding on pipe in the horizontal fixed position. In metal-arc welding, the preferred direction seems, usually, to be from the bottom upward. However, considerable welding, especially of thin or medium thickness pipe, is done in the opposite direction. Ordinarily, more metal per layer is deposited when welding upward, and the requirement that the layers be thin enough to undergo complete grain refinement must be observed. On the other hand, welding downward probably requires a higher degree of manual skill to secure adequate fusion with the side walls and to avoid trapping of slag.

Each layer of deposited weld metal should be thoroughly cleaned prior to the deposition of the following layer. Wire brushing, especially when done with a power-driven brush, is effective in removing the slag deposited by covered electrodes used in arc welding. Surface defects which would otherwise affect the soundness of the weld should be chipped out. The surface of the deposited metal and the faces of the base metal should be prepared for the following layer by removing bumps and sharp corners or grooves which might otherwise be difficult to fill without risk of slag inclusions. In welding for severe service conditions, such cleaning is often done with power-operated chipping tools. See Chapter 10 for further information on the fundamentals of shielded metal-arc welding.

Manual oxy-acetylene welding is used for many of the ferrous and nonferrous metals used in piping systems, although its use generally is confined to small-sized piping, or to work where the clearances around the joints are small. However, the process offers the same advantages of flexibility, simplicity, safety and low maintenance costs as manual shielded metal-arc welding. In addition, the equipment required for its application is less expensive and more portable than that required for the shielded metal-arc process. Consequently, it provides an inexpensive means for welding of piping systems in instances where the lack of electric power facilities or the cost of electric welding equipment precludes the use of arc welding.

As in the case of manual shielded metal-arc welding, oxy-acetylene welding techniques may differ in some details but the fundamentals relating to joint design, number of passes, direction of welding and cleaning are the same. Joint design is discussed elsewhere in this chapter. The number of passes required for welding joints in ferrous piping varies with the wall thickness of the pipe, the position of the pipe when welded, and the size of the welding rod used.

While the methods of depositing weld metal for the various positions are similar to those employed in manual shielded metal-arc welding, the thickness of the deposited layers is usually greater. For joints in low-carbon or low-alloy steel piping that can be rolled, or when the work is in a horizontal position, using the backhand technique, one pass is usually used for wall thicknesses up to

$^{1}/_{8}$ in., two for wall thicknesses $^{2}/_{8}$ to $^{5}/_{8}$ in., three for wall thicknesses $^{5}/_{8}$ to $^{7}/_{8}$ in., and four for wall thicknesses $^{7}/_{8}$ to $1^{1}/_{8}$ inch. Using the forehand technique, the weld is usually deposited in a single pass. With the pipe in the vertical fixed position, the number of passes varies widely. However, for most applications, determination of the number of passes by the rule of one pass for each $^{1}/_{8}$ in. thickness of pipe wall is considered good practice.

The number of passes used in welding medium-carbon and high-alloy steels and nonferrous metals varies to a considerable extent because of the diversified effects that the heating and cooling cycles have on the metallurgical structures of the metals.

With regard to direction of welding, the backhand technique in oxy-acetylene welding usually contemplates starting at the top of the pipe and finishing at the bottom, whereas the forehand technique contemplates starting at the bottom of the pipe and working upward to the top. See Chapter 5 for further information on the fundamentals of this process.

The use of automatic and semi-automatic *submerged arc welding* for piping is rapidly increasing. This process is generally applicable to longitudinal seam welding of rolled plate piping, circumferential welds on piping 8 in. in diameter and larger, and straight fillet welds of fabricated plate specials. In addition, semi-automatic submerged arc welding is also being used to some extent in welding intersection joints. Rather extensive shop facilities are required for this process, including 600- to 1200-amp., d.c. generators or a.c. transformers, work positioners and, for the fully automatic method, structures for supporting and positioning the welding head. Backing rings are generally used for groove welds, or, as an alternative, the root pass of the weld may be made manually. Accurate preparation, and good fit-up of the joints are essentials since the process allows little, if any flexibility to compensate for irregularities on this score.

Submerged arc welding has been applied to a wide variety of steels, including low-carbon and medium-carbon steels, and some of the low-, medium- and high-alloy steels with special properties of heat resistance, corrosion resistance and high strength. See Chapter 13 for further information on the fundamentals of this process.

Atomic hydrogen welding is occasionally used for the joining of light gage carbon steel, alloy steel and nonferrous metals including aluminum, nickel and copper and their alloys. Special equipment is required for its application, and to obtain the advantages of its adaptability for welding complex sections, such as jacketed piping constructed of dissimilar metals, considerable skill is required on the part of the welder. See Chapter 11 for further information on the fundamentals of this process.

Inert-gas metal-arc welding was developed early during the war and has become a dependable method for welding piping materials that are difficult to weld by other processes, particularly aluminum, magnesium and high chromium-nickel alloys. It has been used to a limited extent for welding copper. For practical reasons the thinnest section that can be hand-welded is approximately $^{1}/_{32}$ inch. The maximum thickness that may be welded is limited by available equipment and will vary for different metals.

As with other processes, accurate preparation and good fit-up are important considerations. Depending on the metal welded, the cleaning operations preparatory to welding should be carefully performed, and in some cases may require the use of chemical treatments, especially on aluminum and magnesium because of their tendency to oxidize readily. Some type of backing is beneficial, but, depending again on the metal welded, care should be exercised in the selection of such material from the standpoint of its effect on the welding.

In general, welding procedures follow the same general principles common to other processes, and equivalent welder skill is essential for satisfactory results. For further information on the fundamentals of inert-gas metal-arc welding see Chapter 12.

Brazing, braze-welding and *soft-soldering* as applied to components of piping systems have been discussed briefly elsewhere in this chapter (Design). Further information may be found in Chapters 22 and 23. The principles therein outlined for joint preparation, filler metal, fluxes and heating are applicable to piping.

Shrinkage and Distortion

As has been pointed out, precise calculations of shrinkage in welded pipe joints are impractical. In general, however, shrinkage values vary directly and principally with the thickness of the heaviest section being welded and the heat input and, inversely, with the degree of restraint imposed by fixtures, if used. The theoretical aspects of the subject of shrinkage and consequent distortion, the control therof, and of the stresses set up in welded joints due to the thermal action or mechanical restraint are treated at length in Chapter 43 of this HANDBOOK.

For practical purposes in pipe welding, the angular distortion in circumferential and in intersecting welds can be controlled, and its extent reduced to a minimum by (1) proper application of the welding procedure, particularly with respect to uniformity of heating, (2) uniform preheating of the parts prior to and during the welding operation and (3) the use of fixtures for holding the parts in fixed relation to each other during welding. The first two of these methods contemplate free movement of the parts and generally result in lower residual stresses, while with the third method, the opposite is true. Residual stresses can be relieved to some extent by peening or by thermal treatment. Distortion can be corrected by the straightening operations hereinafter described.

In fabricating headers or other assemblies containing various types of welded joints in close proximity to one another, the control or distortion due to shrinkage is quite complicated and involves considerations of the layout and fitting of the assemblies, the sequence of welding, positioning of the welds, and the avoidance of heat concentrations, from the standpoint of not only their individual effect, but also their relative effects on the entire assembly. The expedients employed to control such distortion have already been mentioned but their effectiveness is difficult to estimate, and depends on the welder's experience to a very great degree.

Repair of Welds

When a weld is to be repaired, the defect should first be removed by chipping, machining or by oxygen gouging or oxygen cutting, provided these processes are suitable for the metal. After removal of the defect, the surface upon which the repair weld is to be deposited should be so shaped and cleaned that a sound weld may be obtained. If preheating was required in making the original weld, it should be employed also in making the repair. Should there be general sweating of a weld, no attempt to repair it should be made. The entire weld should be removed and the joint rewelded.

Preheating and Stress Relief

Methods Employed.—Preheating may be accomplished by any one of several methods. The simplest, of course, is torch heating. It is recommended, however, that this method be used only for pipe which is of sufficiently small diameter to result in a reasonable degree of temperature uniformity around the circumference and where the heat input due to welding is such that no supplementary heating is required to maintain the desired temperature. Where supplementary heating is required, as is usually the case, it is usually accomplished by electric heating elements wrapped around the pipe ends or by fuel-fired muffle-type furnaces designed to fit around the ends, leaving an open space at the joint for welding. In the case of electric heating, the coils may be designed to heat by conduction and radiation or by induction. In the latter case, the heating current is usually switched off during actual welding, as the induced current in the pipe interferes with the welding.

The most satisfactory method of stress relief is by heating in a furnace, and this is done whenever practical. However, this method is, in general, suitable only for shop-welded subassemblies. Methods which have been used in the field for circumferential butt welds are electric heating by induction with low-frequency electric current (60 cycles or less), electric heating by conduction and radiation with coiled heating elements wrapped around the joint and flame heating with metal or refractory furnaces of the muffle type designed to fit around the joint.

Temperature Control.—The control of temperature in both preheating and stress relief operations is especially important and frequently influences selection of the equipment. If torch heating or muffle-type, gas-fired furnaces are used, control of temperature is generally accomplished by manual regulation of the heating ap-

paratus, and the temperatures are checked by the use of portable pyrometers, or pyrometric cones. If electric heaters are used, control of temperature is accomplished by electrically-operated pyrometers that automatically control the current flow to the heating units, and indicate the temperatures throughout the entire heating cycle. There are also available, with some types of electric heating equipment, electrically-operated program control devices that can be set to automatically control the time-temperature cycle of a stress-relieving operation within any desired limits of apparatus capacity.

In preheating or stress relieving welds in any of the alloys that have air-hardening tendencies, special precautions should be taken to exclude as much as possible the circulation of air around the joint, both during heating and cooling periods. This can be done by positioning the work in a part of the shop where there is little draft and by closing up open ends of the parts being welded to prevent air circulation through the interior of the piping during the heating period. During the cooling cycle the joint should be covered with a suitable insulating jacket immediately after the welding is completed.

Other Thermal Treatment

It is frequently necessary to totally heat treat complete welded piping assemblies not only for stress relief but also to restore the original structure of the metal or to attain other desirable properties. This may involve annealing, normalizing or quenching treatments, depending on the alloy welded, and requires extensive furnace equipment for its application. Such furnaces are usually gas- or oil-fired, pyrometrically controlled and of such construction and proportion as to allow the treatment of a number of assemblies in one charge.

It is beyond the scope of this Chapter to describe in detail these various heat treating procedures as applied to the various metals used in piping, except to state that the work requires the supervision of a competent metallurgist, and rather extensive laboratory equipment for analysis of results.

Distortion in Heat Treating

The temperatures employed in stress relief and other heat-treatment operations are often in a range where the properties of the metals to resist deformation are lowered to an appreciable extent. It is therefore necessary to properly support the welded joint during the stress-relieving operation in a manner that will reduce to a minimum the possibility of deflection in any direction. This can be readily accomplished in the shop by placing adjustable roller-type supports under the parts being welded as near to the joint as possible, allowing sufficient space for the placement of the heating apparatus over the joint. In field work, where the welds are made in position, chain falls or other suitable rigging secured to the building or other supporting structures can be used to accomplish the same purpose.

If stress relief or heat treatment of a number of assemblies is done in a heat-treating furnace, special care should be exercised in placing the assemblies to make sure that they are adequately and uniformly supported in all directions, using temporary structural bracing tack-welded to the assemblies, if necessary, to accomplish this purpose.

Straightening

The welding of piping assemblies, due to the expansion and contraction of the metal, distorts the original setup and alignment of parts to a varied extent, depending upon the metal welded, its size, shape and thickness. Much of the distortion can be controlled during welding, some of it corrected during stress relieving, when used, but in most cases it is found necessary to correct the effect of distortion independently.

One method employed to correct misalignment is the controlled alternate heating and cooling of areas adjacent to the weld so that the consequent expansion and contraction of the metal will tend to draw the parts into proper alignment. The application of this method is limited to those materials upon which the effect of the alternate heating and cooling is not particularly detrimental to the properties or structure of the metal. To illustrate the elements of this method, assume that a length of reasonably straight pipe is clamped firmly at one end to a rigid table. If an area for a length of 6 in. or more is heated around the pipe adjacent to the clamping device to a red heat and

then a stream of cold water suddenly applied to one side of the pipe, the sudden contraction will cause the free end of the pipe to deflect in the direction of the side of the pipe thus cooled.

It is readily seen that the application of heat and of the cooling medium requires considerable skill and judgment, if satisfactory results are to be obtained. Such skill is only acquired through experience since there is no method that has as yet been devised by which the deflection resulting from such heating and cooling can be precisely calculated.

Another way of correcting misalignment, which has wide application to assemblies that have been furnace annealed or normalized, is to set up the assembly in a facing head with the normal axis of the piece in line with the center lines of the machine, and then machine the flanges or ends so that their faces are square with the normal axis of the pipe and with each other, and meet the over-all dimensional requirements of the piece.

The foregoing methods of squaring and aligning are of course applicable in cases where the assemblies after welding are distorted to a considerable extent. Another method of correcting misalignment is by the gradual application of force, commonly known as *cold pulling*. This method has limited application, however, due to the possibility of setting up excessive stress concentrations in an assembly, and should be employed only in cases where the effect of such stress concentrations would be negligible.

The final step in the straightening operation is the checking of all parts and dimensions of the assembly with the requirements of the drawing from which the assembly was constructed. While this procedure is essentially a function of inspection, much additional handling can be avoided if the work is done before the assembly is removed from the straightening table. This is especially the case on work that is subject to inspection by an outside agency, and is being produced in sufficient volume to require a full-time inspection service.

Cleaning and Finishing

Cleaning of welded piping is of considerable importance. The extent of cleaning and the methods used are of course dependent upon the type of work involved, and may range from merely blowing-out piping by compressed air or steam to pickling and passivating.

For carbon-steel piping where no backing rings are used, care should be taken in the welding procedure to avoid excessive formation of icicles or other projections of the weld metal into the interior of the pipe. Where it is possible such icicles should be removed with a chipping hammer or grinding wheel as the piece is being built, especially so if the roots of the welds become inaccessible after the various connecting parts are assembled.

Flange faces or machined, beveled ends, if adjacent to a weld and likely to be spattered during welding, should be coated with one of the several solutions available on the market for protecting such surfaces against the pelting effects of the spatter, and facilitating its subsequent removal.

Unless piping is heavily scaled as a result of heat treating or other causes, it can be adequately cleaned inside with turbine cleaners which function in much the same manner as boiler tube cleaners. If such equipment is not available, rapping the outside of the piping and blowing it out with air or steam will suffice, although this method takes considerable time and additional handling and is not always reliable.

If the piping has been heavily scaled, it should be sand or shot blasted outside and inside. If sand blasting of the inside is not feasible, turbining may be employed to advantage in some cases provided that special care is taken to make sure that the turbine heads are cutting to the base metal.

The cleaning methods usually employed on alloy-steel piping are similar to those used for carbon-steel piping. Frequently, however, the service for which alloy piping is used requires absolute cleanliness of the piping and the removal of all traces of scale or other foreign matter. In such cases, perhaps the only positive way of assuring cleanliness is by pickling the completed assemblies, either by immersion in pickling vats or by adequate swabbing of the piping with pickling solutions, followed in either case by passivating and then washing with water, depending on the requirements for the particular metal.

The solutions used for pickling or passivating vary with the metals treated, and

the methods employed are dependent on available facilities and the practices of the manufacturer. Reference should be made to standard texts on the subject.

Finishing of welded piping entails thorough inspection, the methods of which are treated in another section of this Chapter. In applying these methods, in so far as they affect workmanship, the following comments are of importance.

Except for in-process inspection of welding most shops arrange for inspection and testing of the completed assembly to follow all other fabricating operations and provide their facilities accordingly.

Non-destructive testing by radiography or magnetic powder methods usually follows postheat treatment operations if such are involved, and is done under controlled laboratory conditions. While some of the larger shops are fully equipped for X-ray examination, its application to pipe work is somewhat limited and it is believed that gamma-ray examination is to be preferred due to the fact that it has more flexible application to piping, especially so in connection with field-welded joints.

Generally speaking, hydrostatic tests, as prescribed by codes and specifications, are applied to assemblies that are fitted with flanged or screwed ends regardless of the ultimate service pressure. If, however, the ends of the assemblies are prepared for field welding, they may be fitted with suitable gaskets and friction clamps that will permit hydrostatic testing up to 60 psi. Tests of this latter sort, however, are only advisable for work subject to low service pressure and the results thereof should be qualified accordingly.

Where the service pressure is severe and full hydrostatic testing on assemblies fitted with welding ends is mandatory, it is necessary to weld temporary heads or caps on the connecting ends of the assemblies so that the required test pressure can be safely applied. In such cases the welding ends of the assemblies are not finished to dimensions until after the testing has been completed.

Air testing is employed to a limited extent in general fabricating practice and usually only to satisfy the requirements of a particular specification. The larger fabricating shops necessarily have facilities for supplying compressed air for other plant services and can therefore usually arrange to test with compressed air up to 100 psi.

INSPECTION AND TESTING

General

The purpose of inspecting and testing welded pipe joints is to provide assurance that the work meets the purchaser's specifications, and that work which is within the scope of a mandatory code complies with the requirements of that code. It is generally accepted that such assurance can be obtained by: (1) The use of a welding procedure that has been proven satisfactory. (2) Control of all operations to make certain that the established procedure will be followed exactly throughout the job. (3) Frequent inspections to make sure that operations are being performed correctly and that materials meet specifications. (4) Occasional confirming tests of actual joints.

Preliminary Inspection

Before any actual welding is done, the inspector should make sure that the welding procedure is one that has been properly qualified, and that its use will produce welds of the proper mechanical, physical and metallurgical characteristics. He must satisfy himself that the welders have, by actual tests, demonstrated their ability to make sound welds when following the prescribed procedures. (See Procedure and Welder Qualification.) He should check the joint design to see that it conforms to the qualified welding procedure. He must assure himself that the materials used are suitable for the purpose, and conform to the requirements of any contract, code or specification governing the work.

Visual Inspection of Work in Progress

An important duty of an inspector is the inspection of individual joints prior to actual welding to make certain that each joint has been properly prepared and fitted. The alignment of parts, fit of the backing ring, if used, and spacing of the pipe ends are especially important. No welder can produce a thoroughly sound joint where the parts to be welded have been poorly fitted.

He must make sufficiently frequent observations to determine whether the prescribed procedure is being properly followed by each welder, particularly as to welding current, number of passes being deposited and cleaning between passes.

Completed welds should be inspected visually for general appearance, noting the amount of weld reinforcement and the presence or absence of undercutting. When the underside of a weld is accessible, it should be inspected to determine whether complete penetration has been obtained and whether there are excessive globules or icicles of metal.

The inspector should make certain that, where required by code or specifications, the welds are stamped with the welder's symbol and any other symbol stamp that may be required.

If preheating or stress relieving of the welded joints is required, the inspector must make sure that the proper temperatures are obtained and held for the required length of time.

Complete inspection includes assurance that the insides of all pipes, valves and fittings are clean and free from blisters, slag, weld spatter, loose mill scale, sand and dirt when erected.

Non-Destructive Tests

Various methods of non-destructive testing have been utilized to a limited extent in the inspection of welded joints in piping systems where the service conditions are severe. Their purpose is to disclose defects, such as incomplete fusion, porosity and cracking, which cannot ordinarily be detected by visual inspection.

Radiographic Inspection.—Radiography, using X-rays or the gamma rays from radium, is occasionally used for examining welds in important work. X-ray inspection requires the use of expensive and comparatively bulky equipment, whereas gamma ray inspection involves the use of easily transported radium or radium-activated materials. Radiographic inspection should be conducted only by one well versed in the art of making radiographs, as well as in the interpretation of the film. This interpretation requires not only a knowledge of welding and weld defects revealed by this method, but also the exercise of considerable judgment as to whether a questionable area is actually defective. Experience is required also, to assure that the testing will be carried out in such a manner as to protect the testing personnel and others against harmful radiations from the source of X-rays or gamma rays employed. Properly applied, the method should reveal defects that amount to 2% or more of the wall thickness. A standard set of radiographs, useful in checking the permissible degree of porosity in piping, may be purchased from the American Society of Mechanical Engineers.

Magnetic Particle Inspection.—This method can be used only on magnetic materials. In application, the part to be examined is first magnetized by an electric current. The surface in the area to be examined is then covered with finely divided iron particles, either by sprinkling dry particles or by applying to the surface a coating of light oil in which the particles are in suspension. A crack or defect in the part, either at or near the surface, causes a discontinuity in the magnetic flux lines. The iron particles collect at that point, outlining the defect. The surface condition is important as the smoother the surface the greater the contrast that results.

For most satisfactory results, the method should be applied only by one who is thoroughly familiar with its characteristics.

Fluorescent Penetrant Inspection.—For inspection of non-magnetic materials with discontinuities extending to the surface, a fluorescent penetrant may be used. The inspection procedure is as follows: Clean part to be inspected, apply penetrant by brush, air spray or immersion, allow penetrant to remain on object for one hour and then wash clean with a water spray, dust on developing powder and inspect the object or area with the use of *black light* in semi-darkness.

Trepanning.—Another method of inspection which is essentially non-destructive though it does require a certain amount of repair welding, consists of the removal of specimens from welds selected more or less at random, and by testing or otherwise examining these specimens. Such examinations serve to indicate the general character of the weld. Also, such inspection has a beneficial psychological effect on the welder, who has no idea from what points the samples will be removed.

The specimen may be a boat-shaped piece cut from the joint by means of a special power-driven spherical saw; a cylindrical plug cut by means of a power-driven hole-saw; a wedge-shaped piece obtained by making two intersecting saw cuts, one on each side of and close to the weld. Or a narrow strip may be ob-

tained by making two saw cuts parallel to the run of the pipe and long enough to extend beyond the heat-affected zone on both sides of the weld, and then removing the intervening plate by drilling or chipping the ends free.

After the specimen has been removed, it is ground or sanded, preferably on a surface that extends across the weld, and the prepared surface is then etched. Examination of the etched surface will disclose such defects as cracks, incomplete fusion or slag inclusions.

Destructive Test of Selected Joints

The most thorough method for examining a joint is to remove a short section of pipe containing the weld. This involves the making of two joints in replacing the piece removed, but may be required in certain work. In the *Code for Pressure Piping* it is provided that, by agreement between the purchaser and the manufacturer or contractor, the quality of the work may be checked by removing a joint made by each welder. Such a joint may be given the standard destructive tests, such as the root, face, and side-bend tests.

Hydrostatic Tests

Hydrostatic testing of welded pipe lines is universally used. Extensive systems are often tested by this method in sections, the separation being made by valves, or, if there are flanged joints available, possibly with blind flanges.

As the expansive force of compressed air or other gas is relatively great, and since there is always a possibility of a failure under test, the use of air or other gas for testing is discouraged. It should be employed only under extraordinary circumstances and under competent supervision.

For most work, clean water is used. The temperature of the water should be no lower than that of the atmosphere. Otherwise sweating will result and proper examination will be difficult. Bleeder valves or pet cocks should be provided at the highest point in the line to permit venting of all air in the piping during the filling operation.

The hydrostatic pressure should be applied gradually and should be left on for a sufficient length of time to permit making a complete examination of all welds. The pressure gage should be checked to be sure that it is functioning properly.

The test pressure should be that called for by the governing code, specification or contract. Lacking such instructions, it should be at least one and one-half times the maximum working pressure to which the piping will be subjected. For power piping the test pressure should never be less than 50 psi., nor more than two times the primary service pressure rating of any valves included in the test. Globe valves should not be subjected to a test pressure under the seat greater than one and one-half times the primary service rating. Full pressure, if it is more than one and one-half times, may be applied above the seat or with the valve open.

It may be necessary to protect expansion joints during testing, particularly when testing of the sections of the system is done prior to the completion of the entire system. Expansion joints of the slip type should be secured against possible separation. Other types should be studied to determine whether they need extra protection or support during testing.

Any evidence of leaking or other weakness under test should be marked. Following release of the pressure, defective areas should be repaired and another hydrostatic test made.

Further information on inspection methods and tests will be found in Chapter 42.

Service Tests

The methods of testing described above are designed to assure the quality of the welding before the system is put into service. In addition to such testing and inspection, many engineers place particular reliance on a service test, essentially a trial operation of a system under normal service conditions.

While the procedure for service testing varies with the installation, there are certain precautionary measures, practically always applicable, that should be taken. These include the removal of all temporary test blanks and test connections, where necessary, the checking of all safety devices to make sure that they are in working order, the checking and setting of all valves and regulating devices for proper operation, and the checking of all hangers and anchor structures to make sure that they are functioning properly.

The results required, in so far as the welding of the system is concerned, are a demonstration that the welds are free

from leaks and are capable of withstanding the stresses imposed on them by the service to which they are subjected. The fact that it is usually the contractor's responsibility to repair any leaks that develop during a service test, and to assume the liability for any damage to other work or equipment resulting from such leaks, is an incentive for him to make certain, as the work progresses, that the welds are so made as to be satisfactory for the service conditions.

BIBLIOGRAPHY

1. *Standard Qualification Procedure,* American Welding Society, 1941.

2. *Code for Unfired Pressure Vessels for Petroleum Liquids and Gases,* American Petroleum Institute and American Society of Mechanical Engineers, 1943.

3. *Recommended Rules for Repairs by Fusion Welding to Power Boilers and Unfired Pressure Vessels,* National Board of Boiler and Pressure Vessel Inspectors, 1945.

4. *Boiler Construction Code:* Section I—Power Boilers; Section VIII—Unfired Pressure Vessels; Section IX—Welding Qualifications, American Society of Mechanical Engineers, 1946.

5. *Code for Pressure Piping* (*B31.1*), American Society of Mechanical Engineers, 1947.

6. *Standard Manual on Pipe Welding,* Heating, Piping and Air Conditioning Contractors National Association, (to be published).

CHAPTER 58

STANDARD WELDING SYMBOLS*

SECTION I—BASIC SYMBOLS

101. Arc and Gas Weld Symbols

Arc and gas weld symbols shall be as shown in Fig. 1.

TYPE OF WELD								
BEAD	FILLET	PLUG OR SLOT	GROOVE					
			SQUARE	V	BEVEL	U	J	

Fig. 1—Basic Arc and Gas Weld Symbols

102. Resistance Weld Symbols

Resistance weld symbols shall be as shown in Fig. 2.

TYPE OF WELD			
SPOT	PROJECTION	SEAM	FLASH OR UPSET

Fig. 2—Basic Resistance Weld Symbols

103. Brazing, Forge, Thermit, Induction and Flow Welding Symbols

Brazing, forge, thermit, induction and flow welding shall be indicated by using a process or specification reference in the tail of the welding symbol. (See Article 305 and Fig. 40.)

104. Supplementary Symbols

Supplementary symbols to be used in connection with weld symbols shall be as shown in Fig. 3.

* Prepared by the AWS Committee on Symbols.

WELD ALL AROUND	FIELD WELD	CONTOUR	
		FLUSH	CONVEX
○	●	—	⌒

Fig. 3—Supplementary Symbols

105. Elements of a Welding Symbol

This standard makes a distinction between the terms *weld symbol* and *welding symbol*. The *weld symbol* is the ideograph used to indicate the desired type of weld. The assembled *welding symbol* consists of the following eight elements, or such of these elements as are necessary:

Reference line.
Arrow.
Basic weld symbols.
Dimensions and other data.
Supplementary symbols.
Finish symbols.
Tail.
Specification, process, or other references.

106. Standard Location of Elements of a Welding Symbol

The elements of a welding symbol shall have standard locations with respect to each other as shown in Fig. 4.

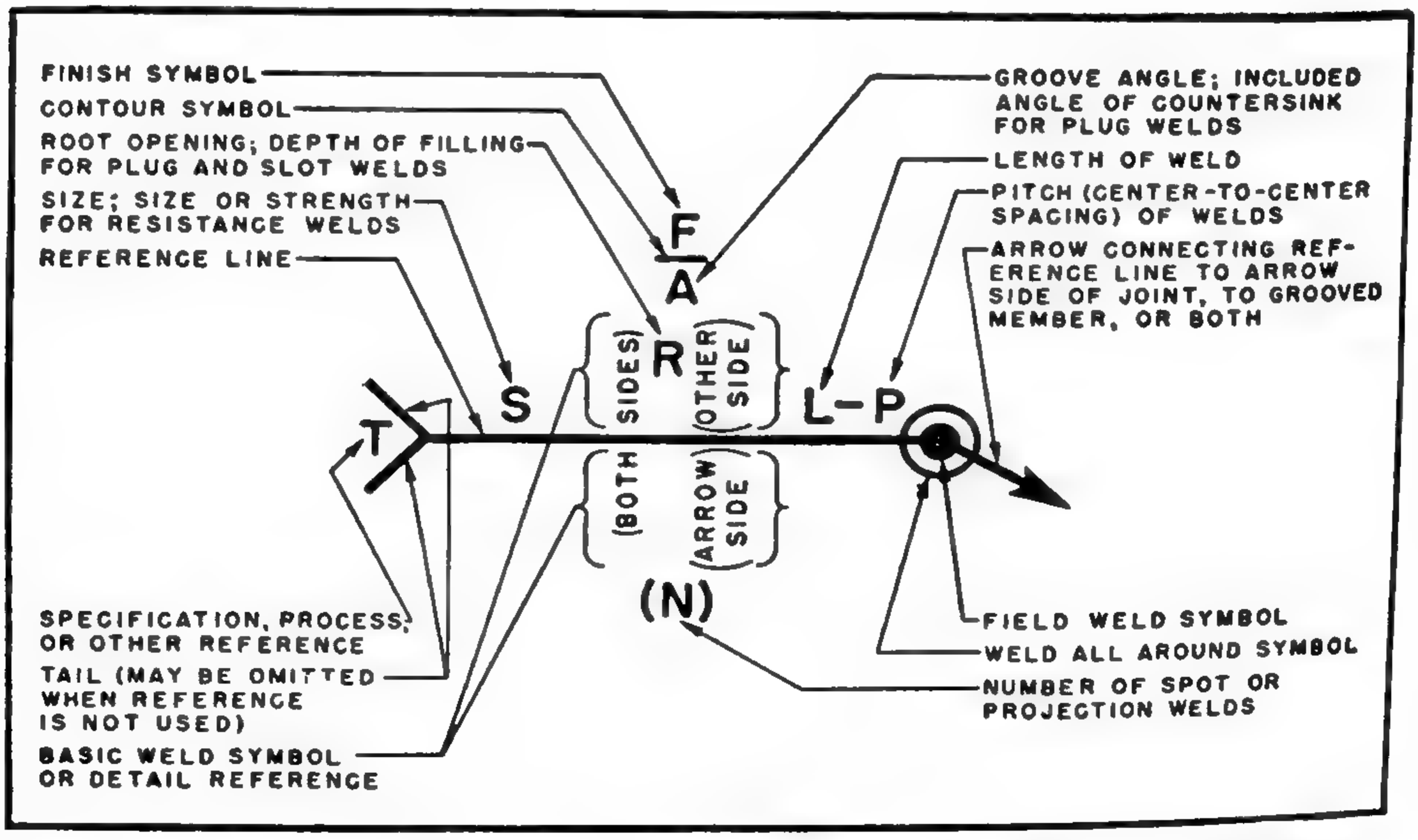


Fig. 4—Standard Location of Elements of a Welding Symbol

SECTION II—BASIC TYPES OF JOINTS AND WELDS

201. Basic Types of Joints

The basic types of joints are shown in Fig. 5 and the types of welds by which the members are frequently joined are listed thereon.

202. Basic Types of Welds

The basic types of welds indicated by the basic weld symbols are illustrated in Figs. 6 to 12 and 15 to 19, inclusive.

SECTION III—GENERAL PROVISIONS

301. Location Significance of Arrow

(*a*) In the case of groove, fillet, and flash or upset welding symbols, the arrow shall connect the welding symbol reference line to one side of the joint, and this side shall be considered the *arrow side* of the joint. The side opposite the arrow side of the joint shall be considered the *other side* of the joint. (See Figs. 6 to 12 inclusive and Fig. 19.)

(*b*) In the case of plug, slot, spot, seam and projection welding symbols, the arrow shall connect the welding symbol reference line to the outer surface of one of the members of the joint at the center line of the desired weld. The member to which the arrow points shall be considered the *arrow-side* member. The other member of the joint shall be considered the *other-side* member. (See Figs. 15 to 18, inclusive.)

(*c*) When a joint is depicted by a single line on the drawing and the arrow of a welding symbol is directed to this line, the arrow side of the joint shall be considered as the near side of the joint in accordance with the usual conventions of drafting. (See Figs. 6 to 12, inclusive and Fig. 19.)

(*d*) When a joint is depicted as an area parallel to the plane of projection in a drawing and the arrow of a welding symbol is directed to that area, the *arrow-side* member of the joint shall be considered as the near member of the joint in accordance with the usual conventions of drafting. (See Figs. 15 to 18, inclusive.)

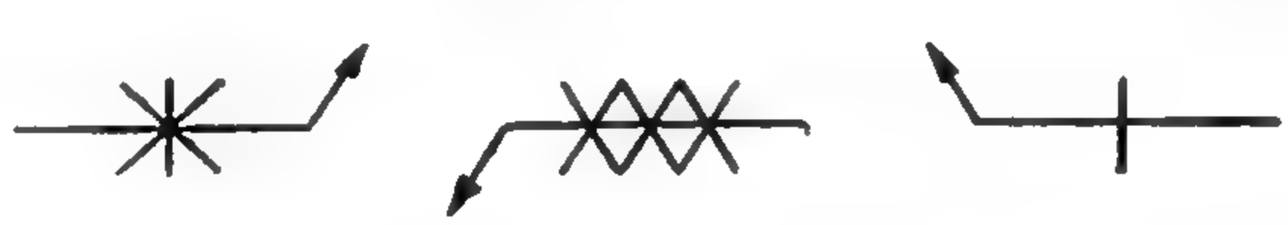
302. Location of Weld with Respect to Joint

(*a*) Welds on the arrow side of the joint shall be shown by placing the weld symbol on the side of the reference line toward the reader, thus: (See also Figs. 6*A*, 8*A*, 9*A*, 10*A*, 11*A*, 12*A*, 15*A*, 16*A* and 18*A*.)

(*b*) Welds on the other side of the joint shall be shown by placing the weld symbol on the side of the reference line away from the reader, thus: (See also Figs. 6*B*, 8*B*, 9*B*, 10*B*, 11*B*, 12*B*, 15*B*, 16*B* and 18*B*.)

(*c*) Welds on both sides of the joint shall be shown by placing weld symbols on both sides of the reference line, toward and away from the reader, thus: (See also Figs. 7, 8*C*, 9*C*, 10*C*, 11*C* and 12*C*.)

(*d*) Spot, seam, flash and upset weld symbols have no arrow-side or other-side significance in themselves, although supplementary symbols used in conjunction therewith may have such significance. (See Articles 301, 906, 1007 and 1202.) Spot, seam, flash and upset weld symbols shall be centered on the reference line, thus: (See also Figs. 17 and 19.)



303. Method of Drawing Symbols

Symbols may be drawn mechanically or freehand, as desired.

304. Use of Inch, Degree and Pound Marks

Inch, degree and pound marks may be used on welding symbols or not, as desired, except that inch marks shall be used for indicating the diameter of spot and projection welds and the width of seam welds, when such welds are specified by linear dimension.

305. Location of Specification, Process or Other References

When a specification, process or other references is used with a welding symbol, the reference shall be placed in the tail, thus:

306. Use of Symbols Without References

When desired, symbols may be used without specification, process or

other references in the following instances:

(*a*) When a note such as the following appears on the drawing: "Unless otherwise designated, all welds are to be made in accordance with Specification No. —."

(*b*) When the welding procedure to be used is prescribed elsewhere.

307. Use of General Notes

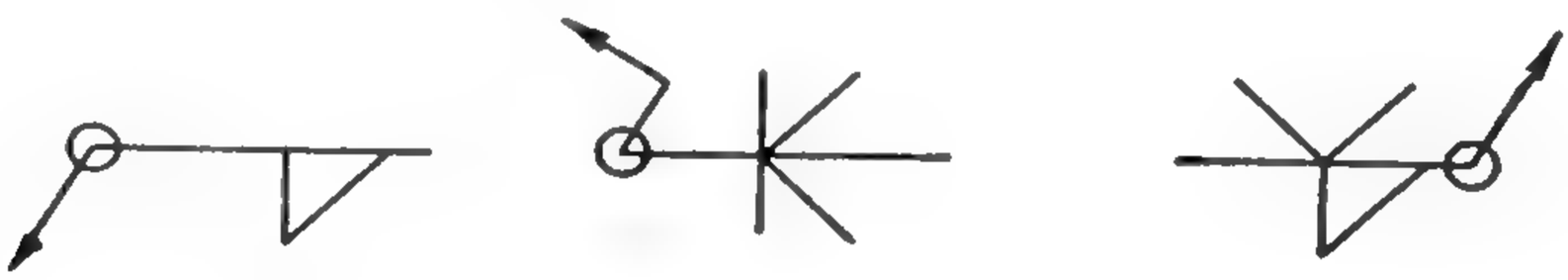
When desired, general notes such as the following may be placed on a drawing to provide detailed information pertaining to the predominating welds, and this information need not be repeated on the symbols.

"Unless otherwise indicated, all fillet welds are $^{5}/_{16}$ inch size."

"Unless otherwise indicated, root openings for all groove welds are $^{3}/_{16}$ inch.

308. Use of Weld-All-Around Symbol

Welds extending completely around a joint shall be indicated by means of the weld-all-around symbol, thus:



309. Use of Field Weld Symbol

Field welds (welds not made in a shop or at the place of initial construction) shall be indicated by means of the field weld symbol, thus:

310. Extent of Welding Denoted by Symbols

Symbols apply between abrupt changes in the direction of the welding or to the extent of hatching or dimension lines, except when the weld-all-around symbol is used. (See Figs. 23, 24, 35*A*, 36*C* and 38*A*.)

311. Weld Proportions

All welds shall be continuous and of user's standard proportions unless otherwise indicated.

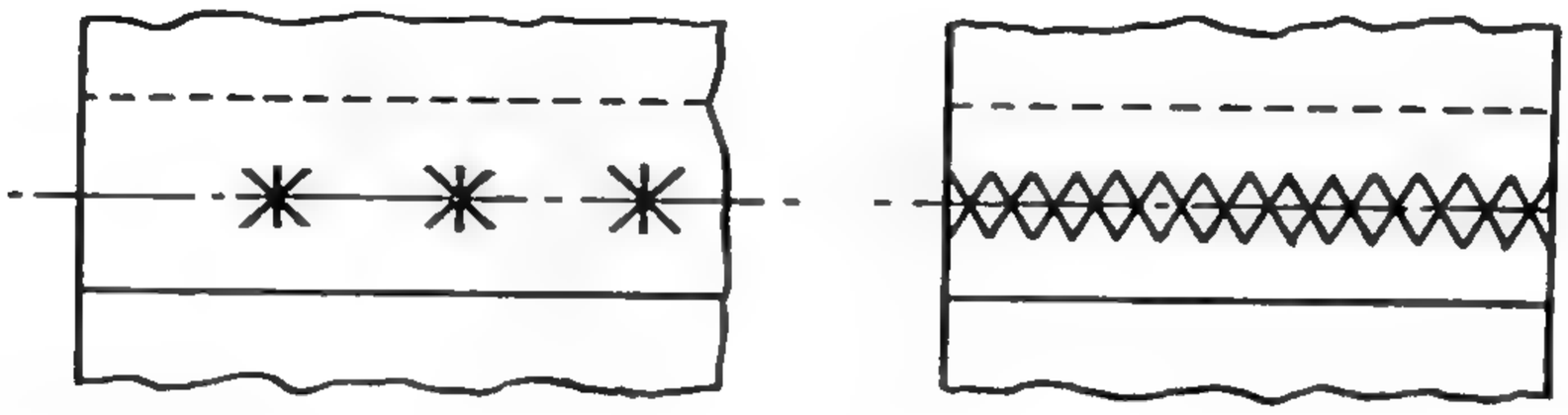
312. Finishing of Welds

Finishing of welds, other than cleaning, shall be indicated by suitable contour and finish symbols. (See Arts. 409, 505, 603, 706, 804 and 1202.)

313. Location of Weld Symbols

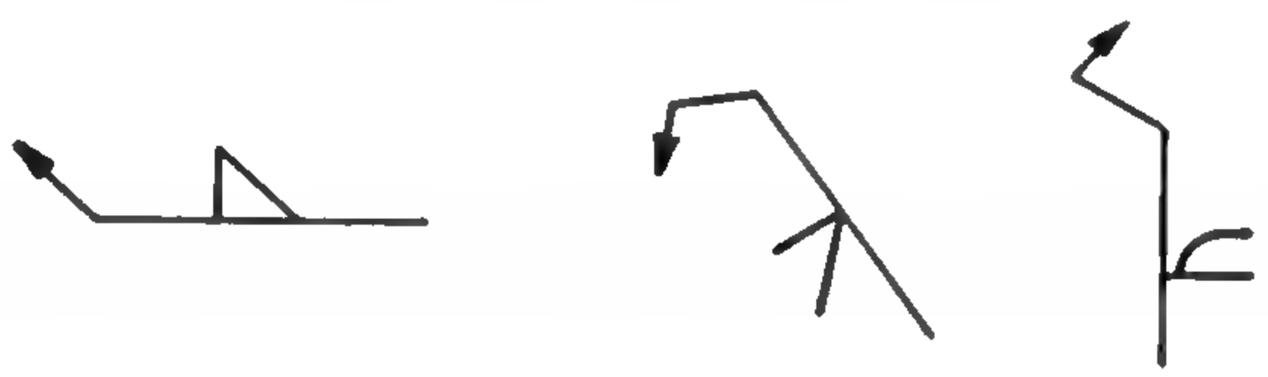
(*a*) Weld symbols, except spot and seam, shall be shown only on the welding symbol reference line and not on the lines of the drawing.

(*b*) Spot and seam weld symbols may be placed directly on drawings at the locations of the desired welds, thus: (See also Fig. 17.)



314. Construction of Fillet and Bevel- and J-Groove Welding Symbols

Fillet and bevel- and J-groove weld symbols shall be shown with the perpendicular leg *always* to the left, thus: (See also Figs. 6, 7, 9 and 11.)

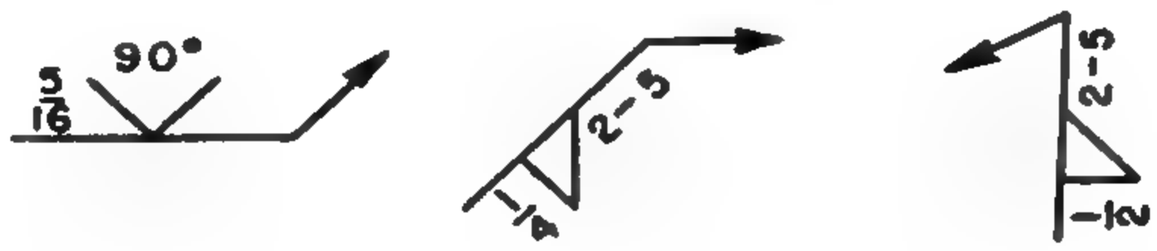


315. Use of Break in Arrow of Bevel- and J-Groove Welding Symbols

When a bevel- or J-groove weld symbol is used, the arrow shall point with a definite break toward the member which is to be chamfered, thus: (See also Figs. 9 and 11.) (In cases where the member to be chamfered is obvious, the break in the arrow may be omitted.)

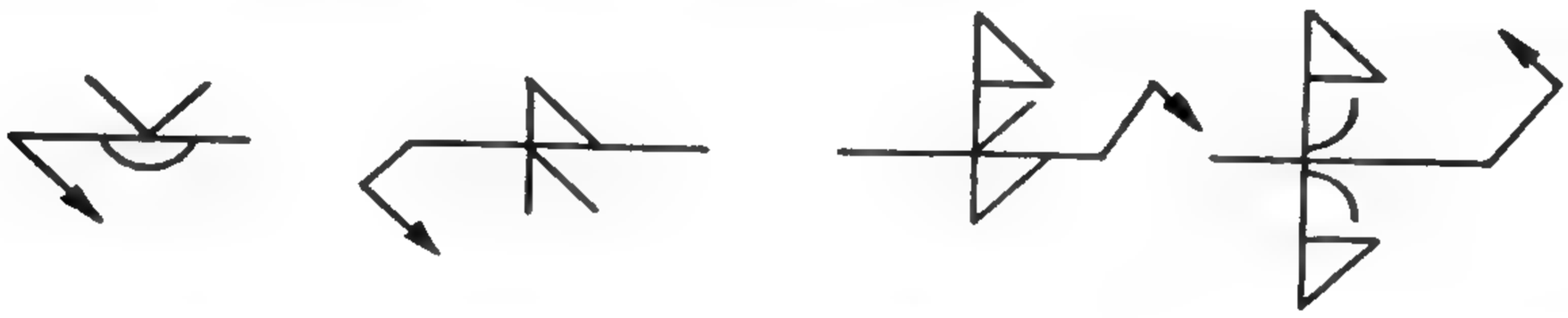
316. Reading of Information on Welding Symbols

Information on welding symbols shall be placed to read from left to right along the reference line in accordance with the usual conventions of drafting, thus:



317. Combined Weld Symbols

For joints having more than one weld, a symbol shall be shown for each weld, thus: (See also Figs. 20 and 27.)



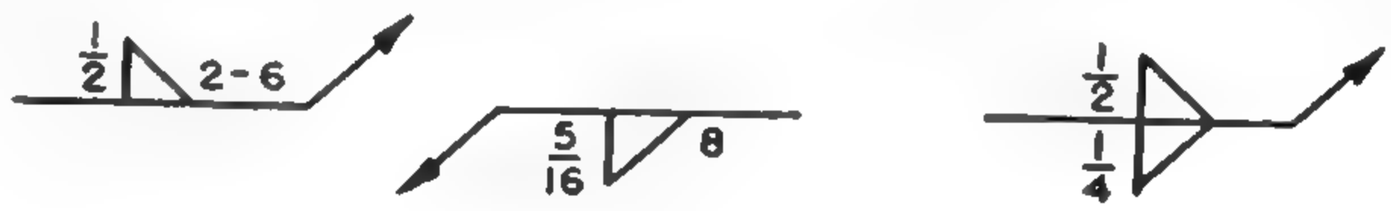
318. Designation of Special Types of Welds

When the basic weld symbols are inadequate to indicate the desired weld, the weld shall be shown by a cross section, detail or other data, with a reference thereto on the welding symbol, observing the usual location significance, thus:

SECTION IV—FILLET WELDS

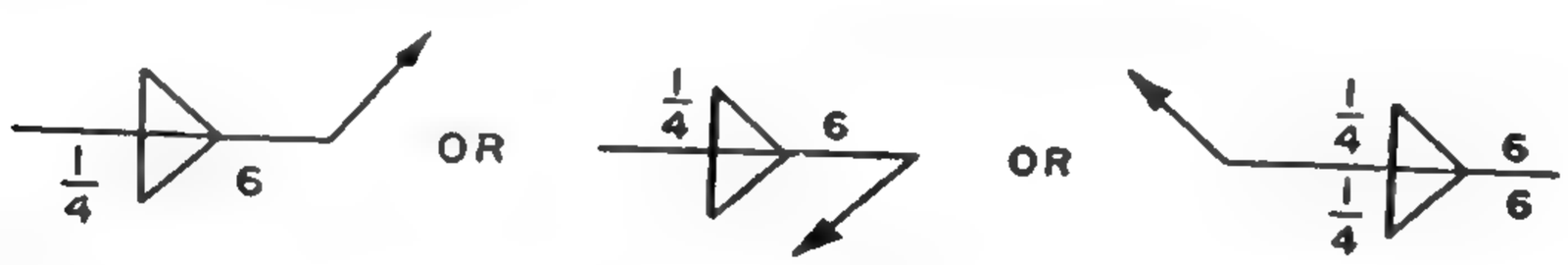
401. General

(*a*) Dimensions of fillet welds shall be shown on the same side of the reference line as the weld symbol, thus: (See also Figs. 21, 22 and 23.)

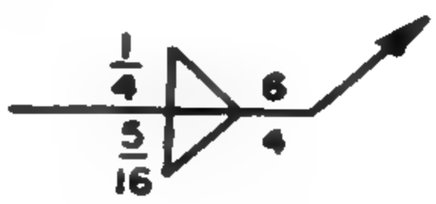


(*b*) When no general note governing the dimensions of fillet welds appears on the drawing, the dimensions of fillet welds on both sides of the joint shall be shown as follows:

(1) When both welds have the same dimensions, one or both may be dimensioned, thus:



(2) When the welds differ in dimensions, both shall be dimensioned. thus:



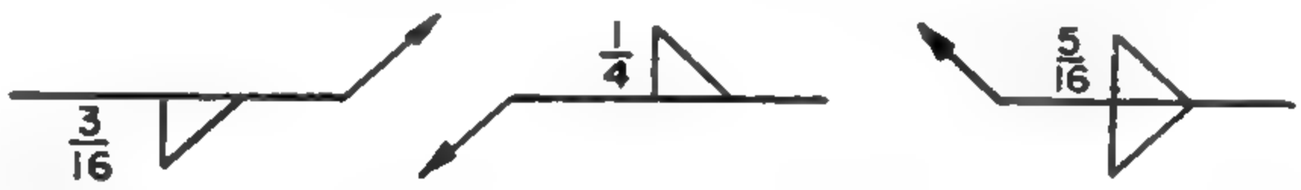
(*c*) When there appears on the drawing a general note governing the dimensions of fillet welds, such as "All fillet welds $^{5}/_{16}$ in. size unless otherwise noted," the dimensions of fillet welds on both sides of the joint shall be indicated as follows:

(1) When both welds have dimensions governed by the note, neither need be dimensioned, thus:

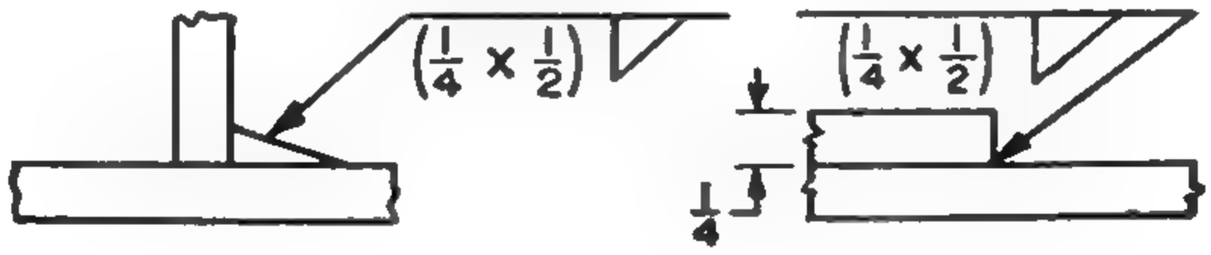
(2) When the dimensions of one or both welds differ from the dimensions given in the general note, both welds shall be dimensioned, thus:

402. Size of Fillet Welds

(*a*) The size of a fillet weld shall be shown to the left of the weld symbol, thus: (See also Figs. 21*A*, 21*B*, 21*C* and 21*D*.)

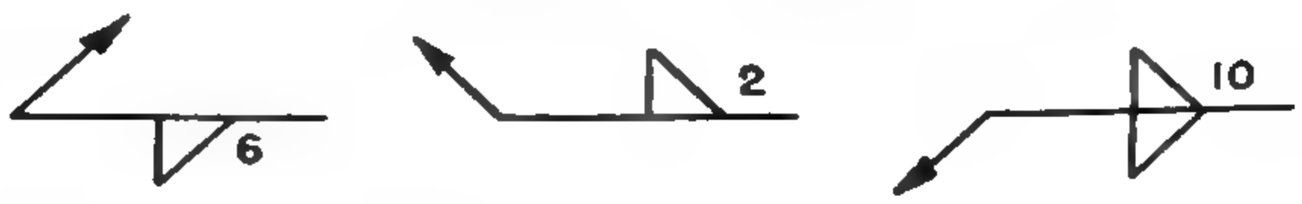


(*b*) The size of a fillet weld with unequal legs, shall be shown in parentheses to the left of the weld symbol, as shown below. Weld orientation is not shown by the symbol and shall be shown on the drawing when necessary. (See also Fig. 21*D*.)



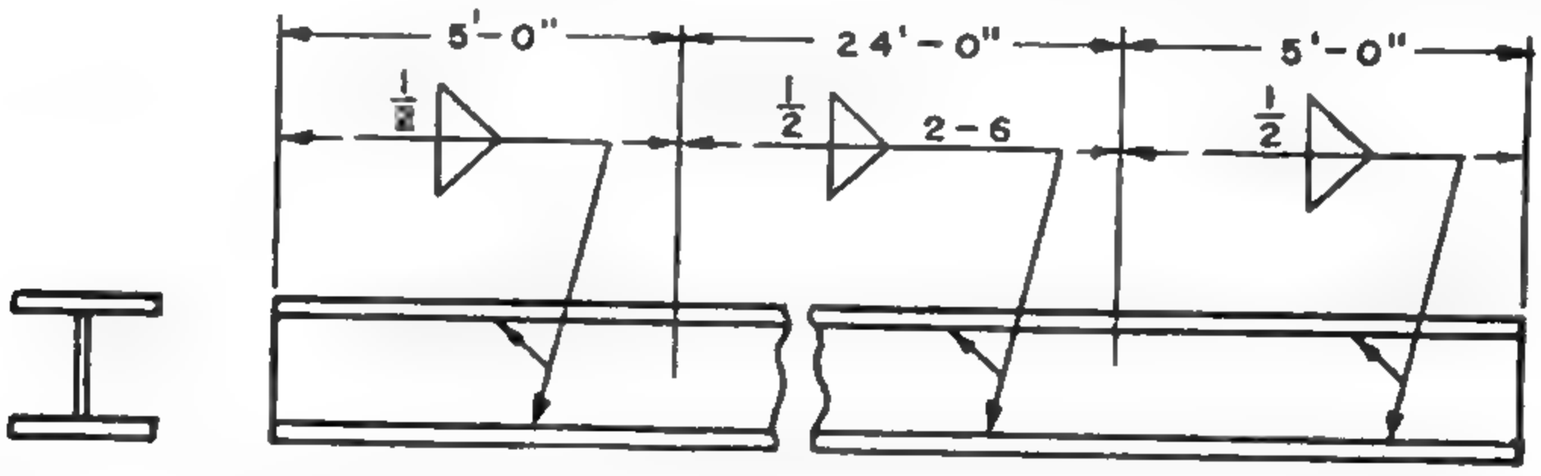
403. Length of Fillet Welds

(*a*) The length of a fillet weld, when indicated on the welding symbol, shall be shown to the right of the weld symbol, thus: (See also Fig. 21*F*.)



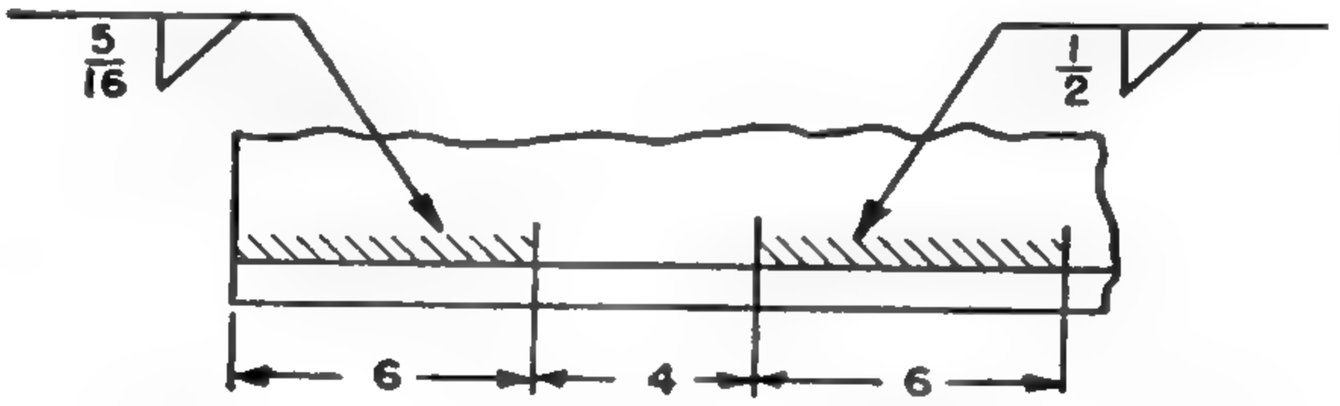
(*b*) When fillet welding extends for the full distance between abrupt changes in the direction of the welding (see Article 310), no length dimension need be shown on the welding symbol. (See Fig. 21*E*.)

(*c*) Specific lengths of fillet welding may be indicated by symbols in conjunction with dimension lines, thus: (See also Figs. 23*A* and 23*B*.)



404. Extent of Fillet Welding

(*a*) When it is desired to show the extent of fillet welding graphically, one type of hatching with definite end lines shall be used, thus:

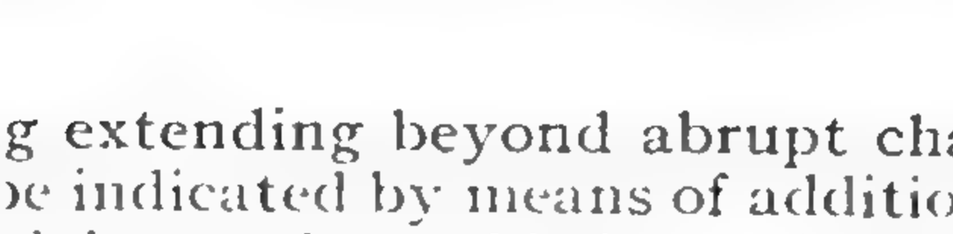


(*b*) Fillet welding extending beyond abrupt changes in the direction of the welding shall be indicated by means of additional arrows pointing to each section of the joint to be welded, as shown in Fig. 24*A*, except when the weld-all-around symbol is used.

405. Dimensioning of Intermittent Fillet Welding

(*a*) The pitch (center-to-center spacing) of intermittent fillet welding shall be shown as the distance between centers of increments on *one* side of the joint. (See Fig. 22.)

(*b*) The pitch (center-to-center spacing) of intermittent fillet welding shall be shown to the right of the length dimension, thus: (See also Fig. 22.)



(*c*) Chain intermittent fillet welding shall be shown thus: (See also Fig. 22*B*.)

(*d*) Staggered intermittent fillet welding shall be shown thus: (See also Fig. 22*C*.)

406. Termination of Intermittent Fillet Welding

(*a*) When intermittent fillet welding is used by itself, the symbol indicates that increments shall be located at the ends of the dimensioned length. (See Fig. 22.)

(*b*) When intermittent fillet welding is used between continuous fillet welding the symbol indicates that spaces equal to the pitch minus the length of one increment shall be left at the ends of the dimensioned length. (See Fig. 23*A*.)

407. Combination of Intermittent and Continuous Fillet Welding

Separate symbols shall be used for intermittent and continuous fillet welding when the two are used in combination. (See Fig. 23*A*.)

408. Fillet Welds in Holes and Slots

Fillet welds in holes and slots shall be shown by means of fillet weld symbols.

409. Surface Contour of Fillet Welds

(*a*) Fillet welds that are to be welded approximately flat-faced without recourse to any method of finishing shall be shown by adding the flush-contour symbol to the weld symbol, observing the usual location significance, thus:

(*b*) Fillet welds that are to be made flat-faced by mechanical means, shall be shown by adding both the flush-contour symbol and the user's standard finish symbol* to the weld symbol, observing the usual location significance, thus:

* Finish symbols used herein indicate the method of finishing ("C" = chipping; "G" = grinding; "M" = machining) and not the degree of finish.

(*c*) **Fillet welds that are to be mechanically finished to a convex contour, shall be shown by adding both the convex-contour symbol and the user's standard finish symbol* to the weld symbol, observing the usual location significance, thus:**

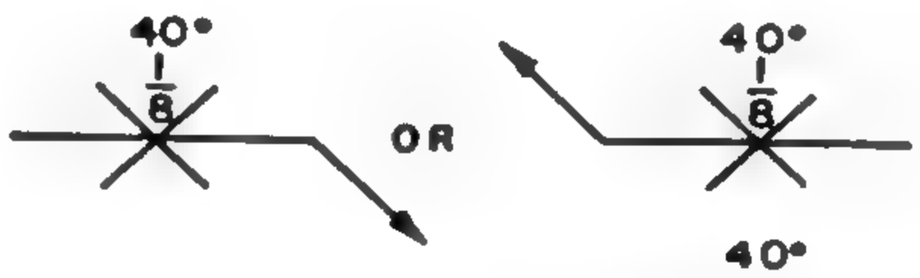
SECTION V—GROOVE WELDS

501. General

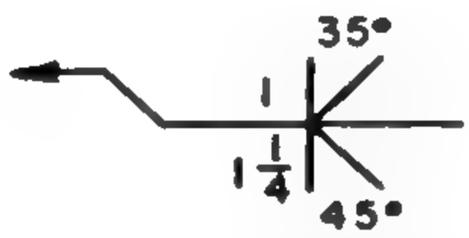
(*a*) Dimensions of groove welds shall be shown on the same side of the reference line as the weld symbol, thus: (See also Fig. 31*B*.)

(*b*) When no general note governing the dimensions of groove welds appears on the drawing, the dimensions of double-groove welds shall be shown as follows:

(1) When both welds have the same dimensions, one or both may be dimensioned, thus:



(2) When the welds differ in dimensions, both shall be dimensioned, thus:



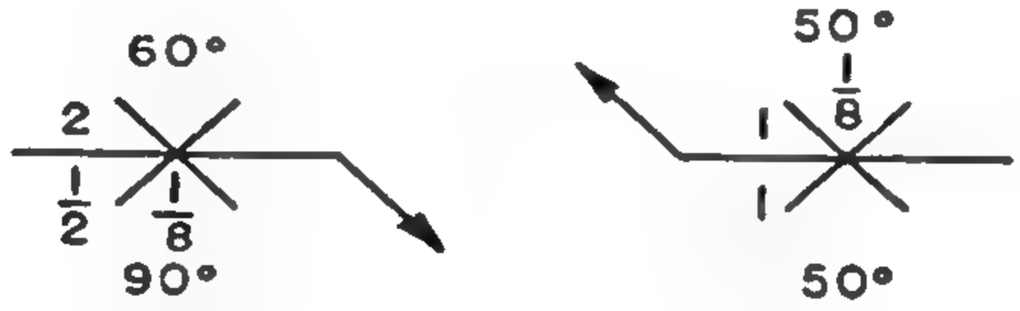
(*c*) When there appears on the drawing a general note governing the dimensions of groove welds, such as "All V-groove welds shall have a 60° groove angle unless otherwise noted," the dimensions of double-groove welds shall be indicated as follows:

(1) When both welds have dimensions governed by the note, neither

* Finish symbols used herein indicate the method of finishing ("C" = chipping; "G" = grinding; "M" = machining) and not the degree of finish.

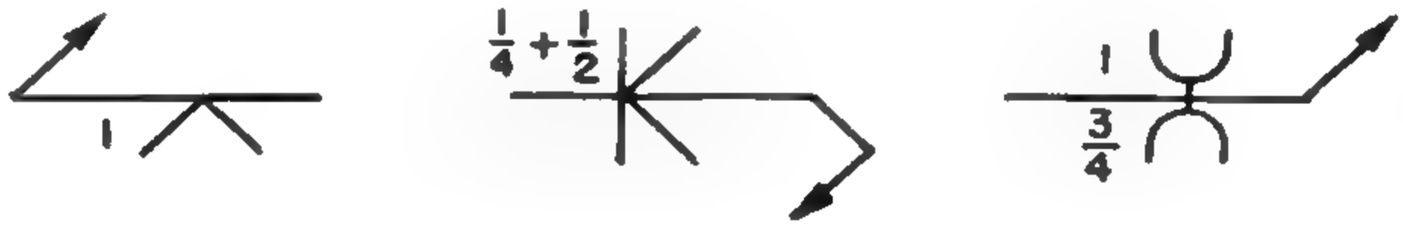
need be dimensioned, thus:

(2) When the dimensions of one or both welds differ from the dimensions given in the general note, both welds shall be dimensioned, thus:



502. Size of Groove Welds

(*a*) The size of groove welds shall be shown to the left of the weld symbol, thus: (See also Figs. 25, 26 and 27.)

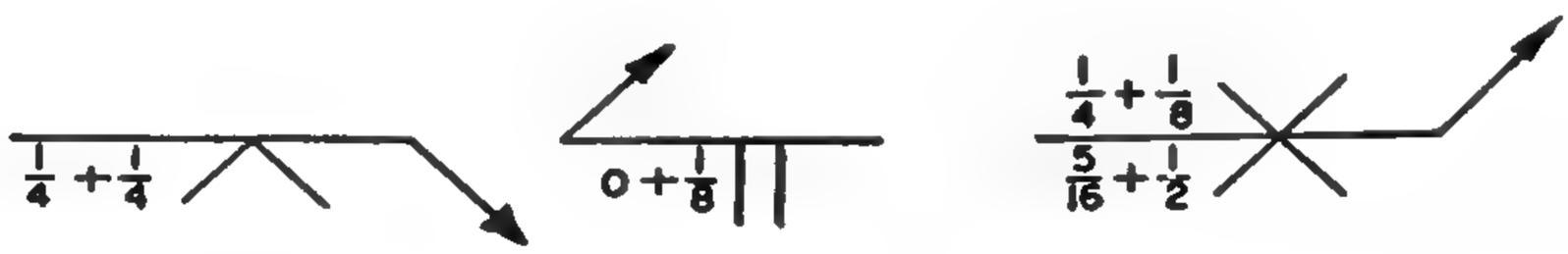


(*b*) The size of groove welds with no specified root penetration shall be shown as follows:

(1) The size of single-groove and symmetrical double-groove welds which extend completely through the member or members being joined, need not be shown on the welding symbol. (See Figs. 25*D* and 25*E*.)

(2) The size of groove welds which extend only partly through the member or members being joined, shall be shown on the welding symbol. (See Figs. 25*A*, 25*C* and 25*F*.)

(*c*) The size of groove welds with specified root penetration shall be indicated by showing both the depth of chamfering and the root penetration, separated by a plus mark and placed to the left of the weld symbol. The depth of chamfering and the root penetration shall read in that order from left to right along the reference line, thus: (See also Figs. 26 and 27.)

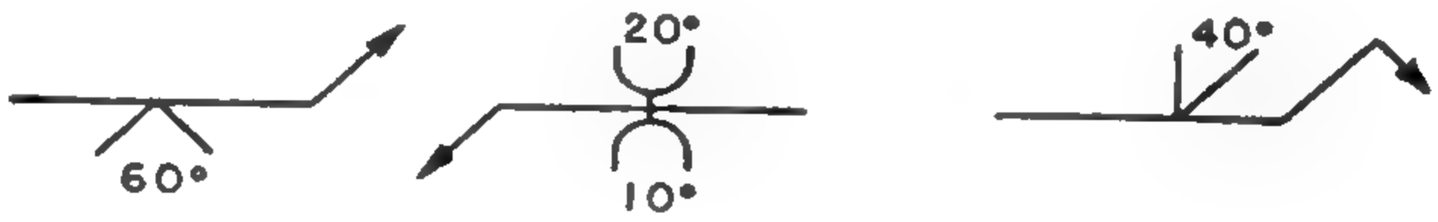


513. Groove Dimensions

(*a*) Root opening of groove welds shall be the user's standard unless otherwise indicated. Root opening of groove welds, when not the user's

standard, shall be shown inside the weld symbol, thus: (See also Fig. 28.)

(*b*) Groove angle of groove welds shall be the user's standard, unless otherwise indicated. Groove angle of groove welds, when not the user's standard, shall be shown thus: (See also Fig. 29.)



(*c*) Groove radii and root faces of U- and J-groove welds shall be the user's standard unless otherwise indicated. When groove radii and root faces of U- and J-groove welds are not the user's standard, the weld shall be shown by a cross section, detail or other data, with a reference thereto on the welding symbol, observing the usual location significance, thus:

504. Designation of Back and Backing Welds

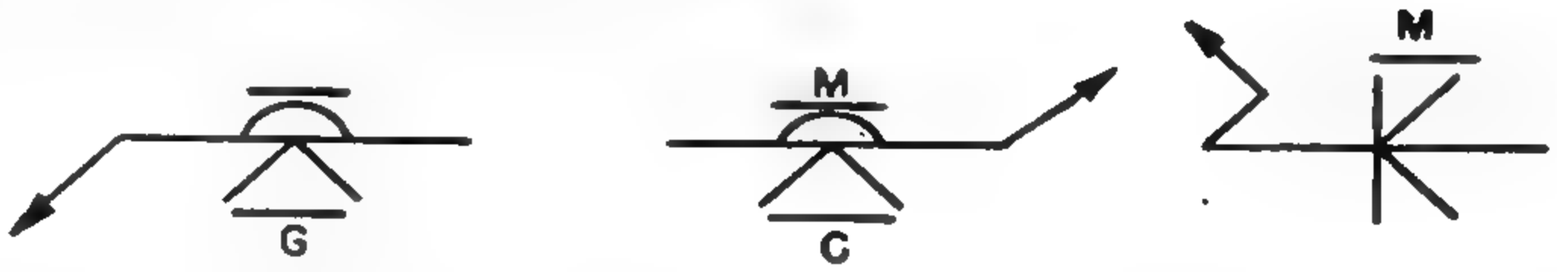
Bead-type back and backing welds of single-groove welds shall be shown by means of the bead weld symbol. (See Art. 602.)

505. Surface Contour of Groove Welds

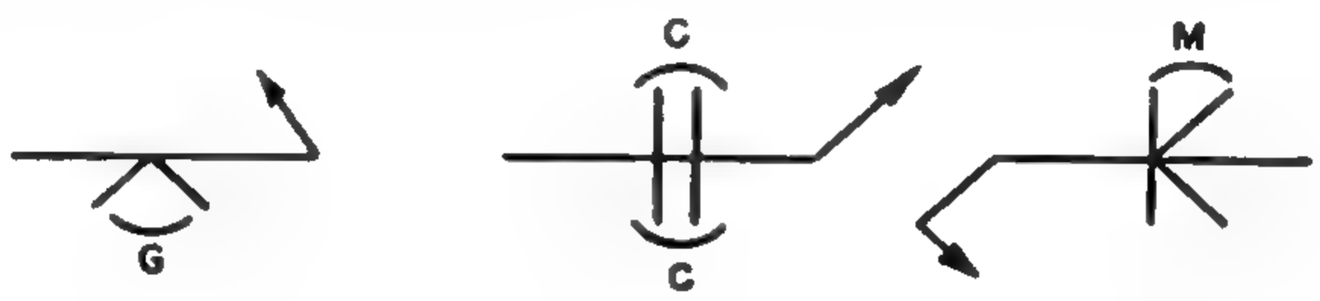
(*a*) Groove welds that are to be welded approximately flush without recourse to any method of finishing shall be shown by adding the flush-contour symbol to the weld symbol, observing the usual location significance, thus: (See also Fig. 30*A*.)

(*b*) Groove welds that are to be made flush by mechanical means shall be shown by adding both the flush-contour symbol and the user's

standard finish symbol* to the weld symbol, observing the usual location significance, thus: (See also Fig. 30*B*.)



(*c*) Groove welds that are to be mechanically finished to a convex contour shall be shown by adding both the convex-contour symbol and the user's standard finish symbol* to the weld symbol, observing the usual location significance, thus: (See also Fig. 30*C*.)



SECTION VI—BEAD WELDS

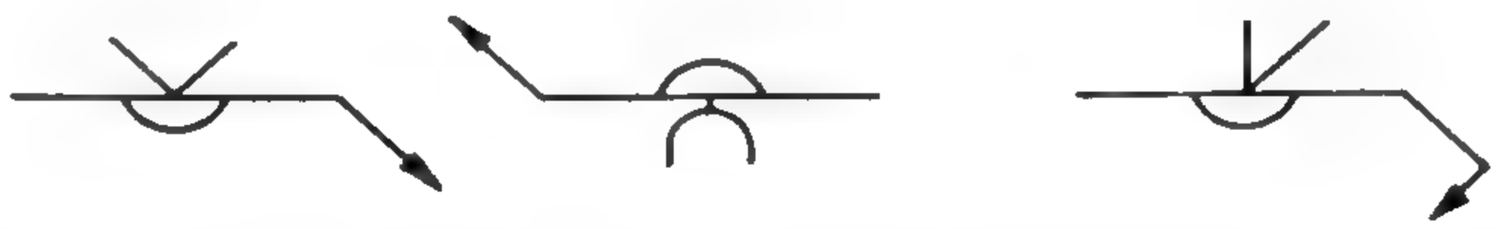
601. General

(*a*) The single bead weld symbol shall be used to indicate bead-type back or backing welds of single-groove welds. (See Fig. 13.)

(*b*) The dual bead weld symbol shall be used to indicate surfaces built up by welding. (See Fig. 14.)

602. Use of Bead Weld Symbol to Indicate Bead-Type Back or Backing Welds

(*a*) Bead welds used as back or backing welds of single-groove welds, shall be shown by placing a single bead weld symbol on the side of the reference line opposite the groove weld symbol, thus: (See also Figs. 13, 20*A* and 20*B*.)



(*b*) Dimensions of bead welds used as back or backing welds shall not be shown on the welding symbol. If it is desired to specify these dimensions, they shall be shown on the drawing.

603. Surface Contour of Back or Backing Welds

(*a*) Back or backing welds that are to be welded approximately flush without recourse to any method of finishing shall be shown by adding the flush-contour symbol to the bead weld symbol, thus:

* Finish symbols used herein indicate the method of finishing ("*C*" = chipping; "*G*" = grinding: "*M*" = machining) and not the degree of finish.

(*b*) Back or backing welds that are to be made flush by mechanical means shall be shown by adding both the flush-contour symbol and the user's standard finish symbol* to the bead weld symbol, thus:

(*c*) Back or backing welds that are to be mechanically finished to a convex contour shall be shown by adding both the convex-contour symbol and the user's standard finish symbol* to the bead weld symbol, thus:

604. Use of Bead Weld Symbol to Indicate Surfaces Built Up by Welding

(*a*) Surfaces built up by welding, whether by single- or multiple-pass bead welds, shall be shown by the dual bead weld symbol, thus: (See also Fig. 14.)

(*b*) The dual bead weld symbol does not indicate the welding of a joint, and hence has no arrow- or other-side significance. This symbol shall be drawn on the side of the reference line toward the reader and the arrow shall point clearly to the surface on which the weld is to be deposited. (See Fig. 14.)

(*c*) Dimensions used in conjunction with the dual bead weld symbol shall be shown on the same side of the reference line as the weld symbol, thus: (See also Fig. 14.)

* Finish symbols used herein indicate the method of finishing ("C" = chipping; "G" = grinding; "M" = machining) and not the degree of finish.

605. Size (Height) of Surfaces Built Up by Welding

(*a*) The size of a surface built up by welding shall be indicated by showing the minimum height of the weld deposit to the left of the weld symbol, thus: (See also Fig. 14*A*.)

(*b*) When no specific height of weld deposit is desired, no size dimension need be shown on the welding symbol.

606. Extent, Location and Orientation of Surfaces Built Up by Welding

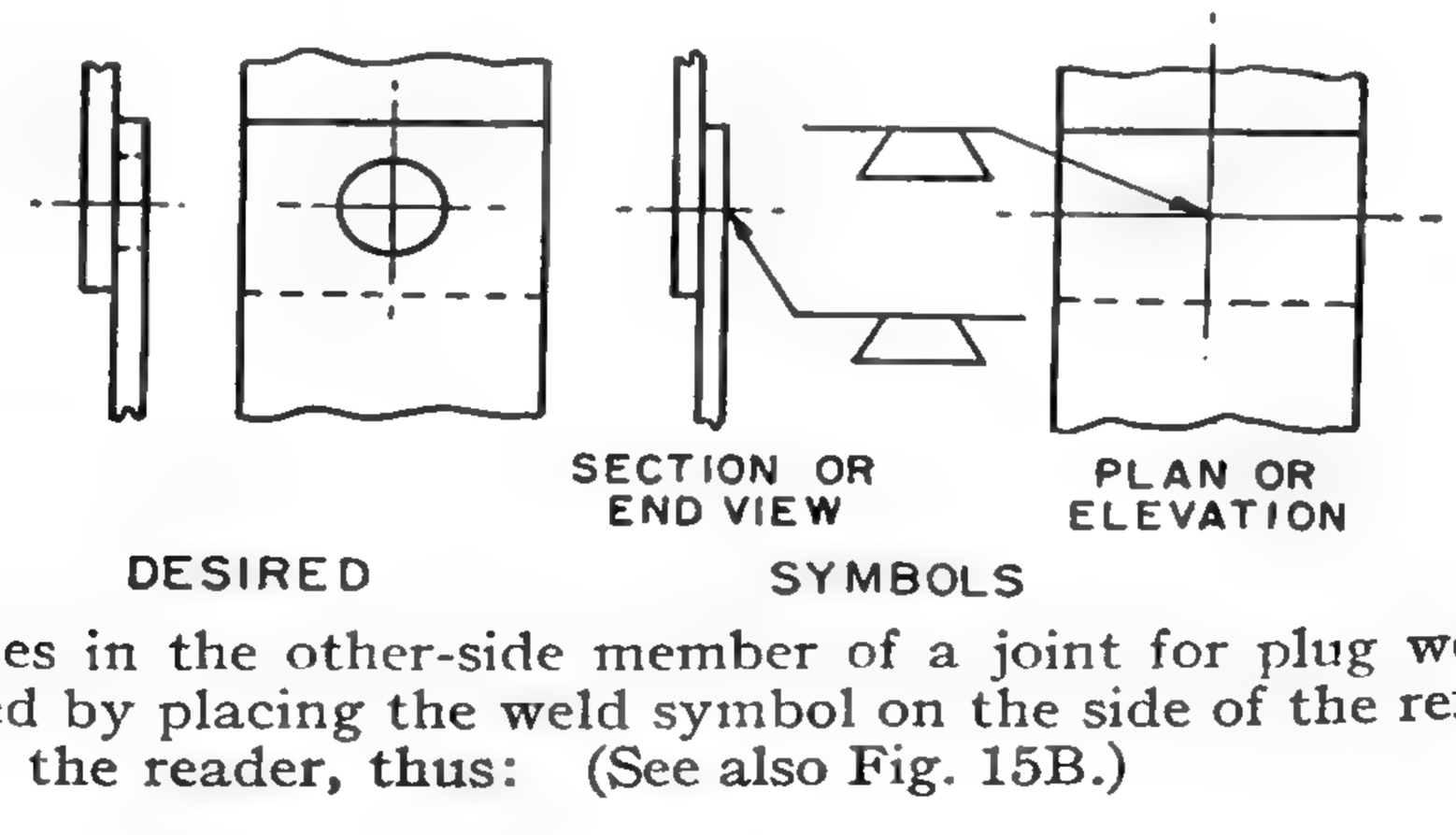
(*a*) When the entire area of a plane or curved surface is to be built up by welding, no dimension other than size (height of deposit) need be shown on the welding symbol. (See Fig. 14*C*.)

(*b*) When a portion of the area of a plane or curved surface is to be built up by welding, the extent, location and orientation of the area to be built up shall be indicated on the drawing. (See Fig. 14*D*.)

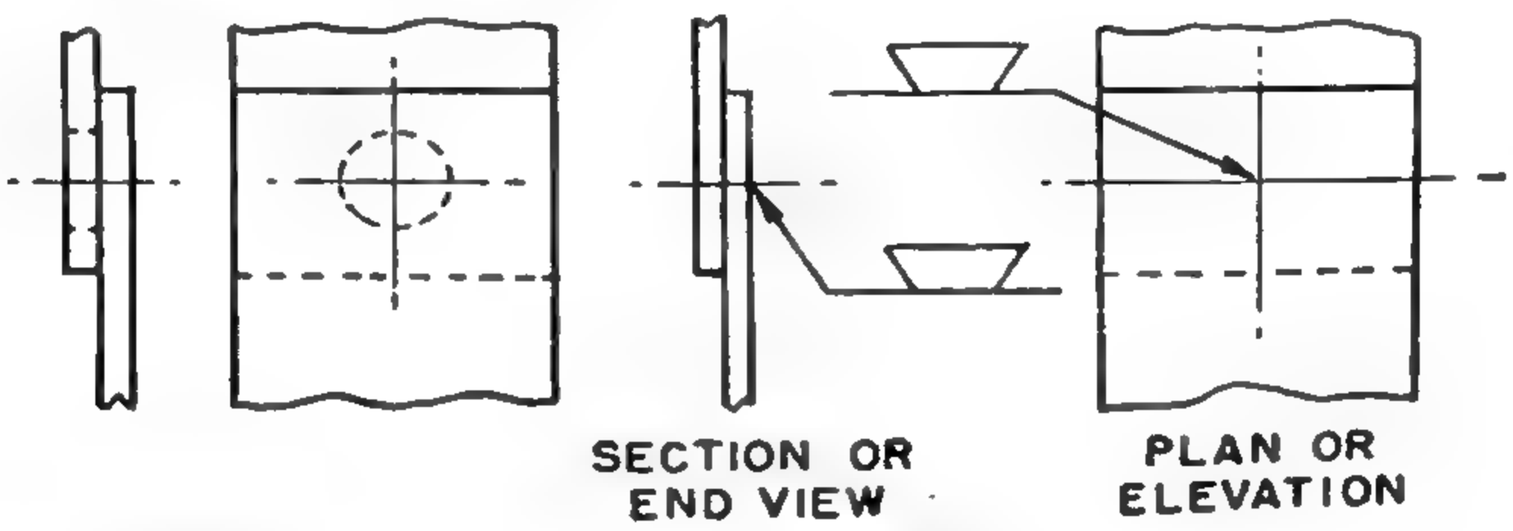
SECTION VII—PLUG WELDS

701. General

(*a*) Holes in the arrow-side member of a joint for plug welding shall be indicated by placing the weld symbol on the side of the reference line toward the reader, thus: (See also Fig. 15A.)



(*b*) Holes in the other-side member of a joint for plug welding shall be indicated by placing the weld symbol on the side of the reference line away from the reader, thus: (See also Fig. 15B.)



(*c*) Dimensions of plug welds shall be shown on the same side of the reference line as the weld symbol, thus: (See also Fig. 32.)

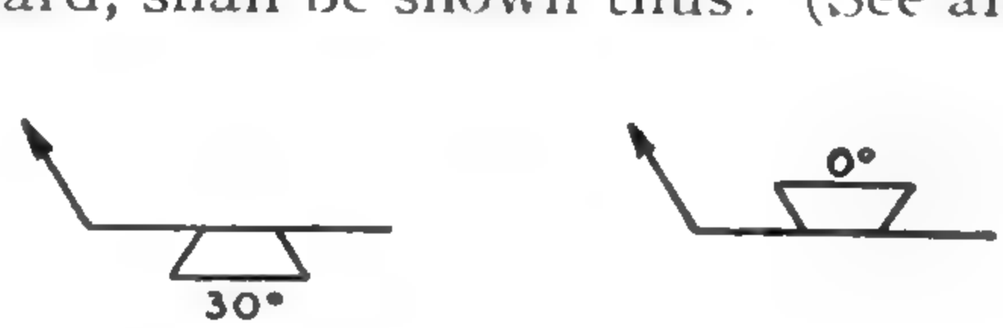
(*d*) The plug weld symbol shall not be used to designate fillet welds in holes. (See Article 408.)

702. Size of Plug Welds

The size of a plug weld shall be shown to the left of the weld symbol, thus: (See also Fig. 32*A*.)

703. Angle of Countersink

(*a*) Included angle of countersink of plug welds shall be the user's standard unless otherwise indicated. Included angle of countersink, when not the user's standard, shall be shown thus: (See also Fig. 32*B*.)



704. Depth of Filling

(*a*) Depth of filling of plug welds shall be complete unless otherwise indicated. When the depth of filling is less than complete, the depth of filling, in inches, shall be shown inside the weld symbol, thus: (See also Fig. 32*C*.)

705. Spacing of Plug Welds

Pitch (center-to-center spacing) of plug welds shall be shown to the right of the weld symbol, thus: (See also Fig. 32*D*.)

706. Surface Contour of Plug Welds

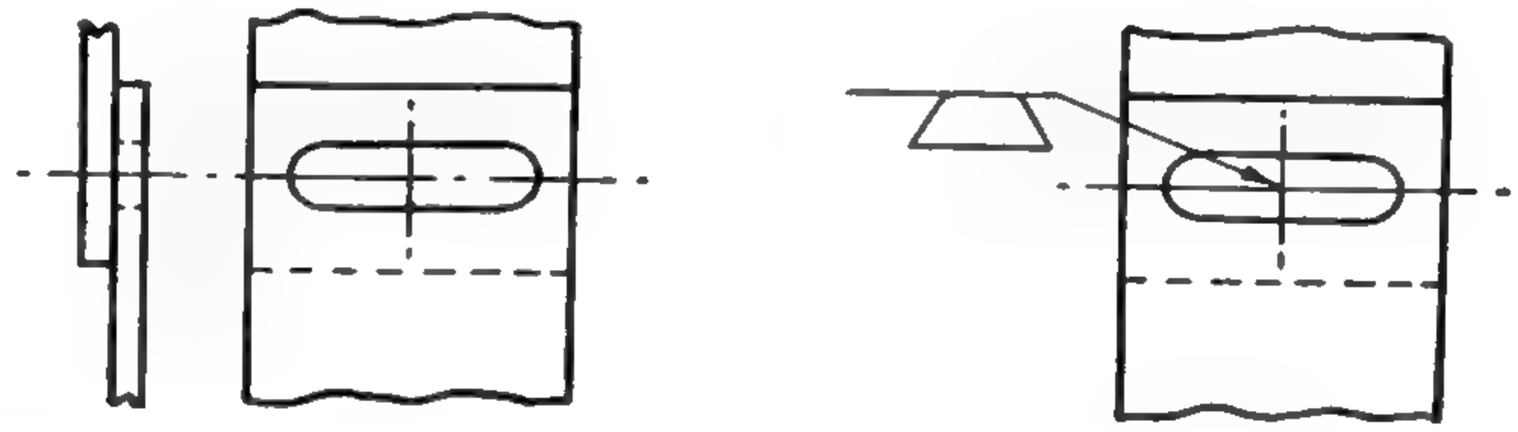
(*a*) Plug welds that are to be welded approximately flush without recourse to any method of finishing shall be shown by adding the flush-contour symbol to the weld symbol, thus:

(*b*) Plug welds that are to be made flush by mechanical means shall be shown by adding both the flush-contour symbol and the user's standard finish symbol* to the weld symbol, thus:

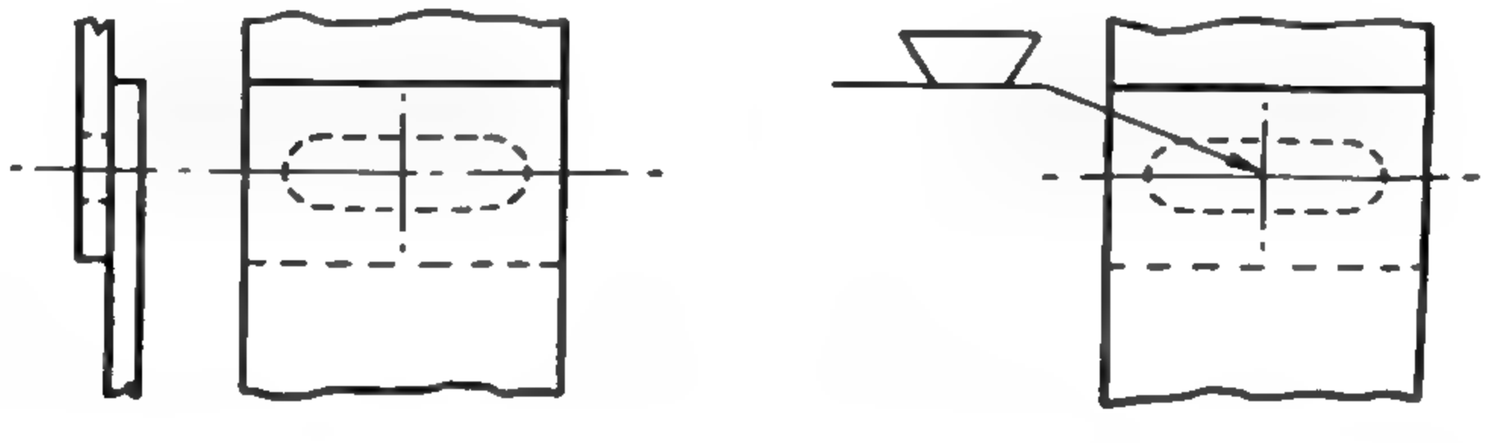
SECTION VIII—SLOT WELDS

801. General

(*a*) Slots in the arrow-side member of a joint for slot welding shall be indicated by placing the weld symbol on the side of the reference line toward the reader, thus: (See also Fig. 16*A*.)



(*b*) Slots in the other-side member of a joint for slot welding shall be indicated by placing the weld symbol on the side of the reference line away from the reader, thus: (See also Fig. 16*B*.)



* Finish symbols used herein indicate the method of finishing ("C" = chipping; "G" = grinding; "M" = machining) and not the degree of finish.

(*c*) Dimensions of slot welds shall be shown on the same side of the reference line as the weld symbol, thus: (See also Fig 33.)

(*d*) The slot weld symbol shall not be used to designate fillet welds in slots. (See Article 408.)

802. Depth of Filling

(*a*) Depth of filling of slot welds shall be complete unless otherwise indicated. When the depth of filling is less than complete, the depth of filling, in inches, shall be shown inside the weld symbol, thus: (See also Fig. 33*B*.)

803. Details of Slot Welds

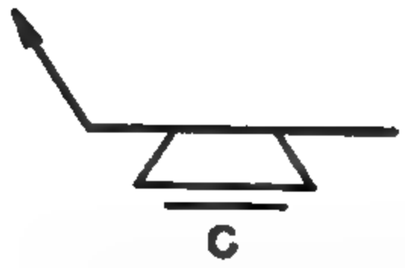
Length, width, spacing, included angle of countersink, orientation and location of slot welds cannot be shown on the welding symbol. These data shall be shown on the drawing or by a detail with a reference thereto on the welding symbol, observing the usual location significance thus: (See also Fig. 33.)

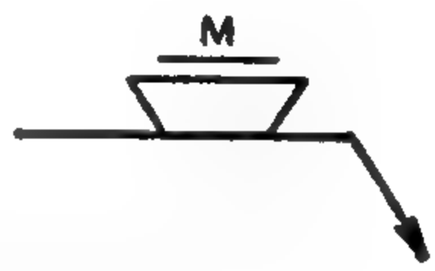
804. Surface Contour of Slot Welds

(*a*) Slot welds that are to be welded approximately flush without recourse to any method of finishing shall be shown by adding the flush-contour symbol to the weld symbol, thus:

(*b*) Slot welds that are to be made flush by mechanical means shall be shown by adding both the flush-contour symbol and the user's standard finish symbol* to the weld symbol, thus:

* Finish symbols used herein indicate the method of finishing ("*C*" = chipping; "*G*" = grinding; "*M*" = machining) and not the degree of finish.





SECTION IX—SPOT WELDS

901. General

(*a*) Spot weld symbols have no arrow- or other-side significance in themselves, although supplementary symbols used in conjunction therewith may have such significance (See Article 906.) Spot weld symbols shall be centered on the reference line. (See Fig. 17*A*.)

(*b*) Dimensions of spot welds may be shown on either side of the reference line.

902. Size of Spot Welds

Spot welds shall be dimensioned by either size or strength, as follows:

(1) The size of spot welds shall be designated as the diameter of the weld expressed decimally in hundredths of an inch, and shall be shown, with inch marks, to the left of the weld symbol, thus: (See also Fig. 34*A*.)

(2) The strength of spot welds shall be designated as the minimum acceptable shear strength in pounds per spot, and shall be shown to the left of the weld symbol, thus: (See also Fig. 34*B*.)

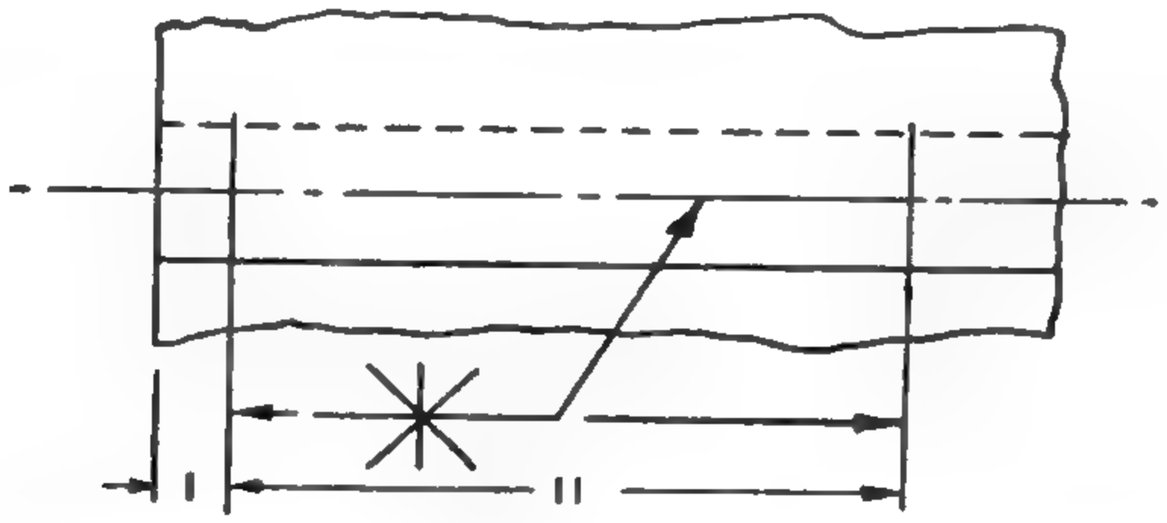
903. Spacing of Spot Welds

(*a*) The pitch (center-to-center spacing) of spot welds shall be shown to the right of the weld symbol, thus: (See also Fig. 34*C*.)

(*b*) When spot weld symbols are shown directly on the drawing, spacing shall be shown by dimensions. (See Fig. 34*D*.)

904. Extent of Spot Welding

When spot welding extends less than the distance between abrupt changes in the direction of the welding, or less than the full length of the joint (see Article 310), the extent shall be dimensioned, thus: (See also Fig. 35*A*.)



905. Number of Spot Welds

When a definite number of spot welds is desired in a certain joint, the number shall be shown in parentheses either above or below the weld symbol, thus: (See also Fig. 35*B*.)

906. Flush Spot-Welded Joints

When the exposed surface of one member of a spot-welded joint is to be flush, that surface shall be indicated by adding the flush-contour symbol to the weld symbol, observing the usual location significance, thus:

SECTION X—SEAM WELDS

1001. General

(*a*) Seam weld symbols have no arrow- or other-side significance in themselves, although supplementary symbols used in conjunction therewith may have such significance. (See Article 1007.) Seam weld symbols shall be centered on the reference line. (See Fig. 17 *B*.)

(*b*) Dimensions of seam welds may be shown on either side of the reference line.

1002. Size of Seam Welds

Seam welds shall be dimensioned by either size or strength as follows:

(1) The size of seam welds shall be designated as the width of the weld expressed decimally in hundredths of an inch, and shall be shown, with inch marks, to the left of the weld symbol, thus: (See also Fig. 36*A*.)

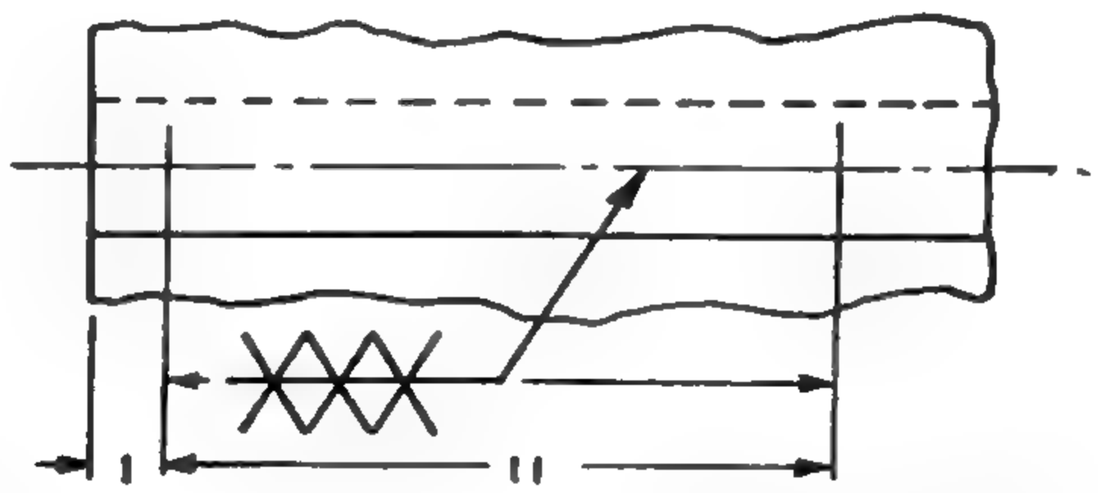
(2) The strength of seam welds shall be designated as the minimum acceptable shear strength in pounds per linear inch, and shall be shown to the left of the weld symbol, thus: (See also Fig. 36*B*.)

1003. Length of Seam Welds

(*a*) The length of a seam weld, when indicated on the welding symbol, shall be shown to the right of the weld symbol, thus: (See also Fig. 36*A*.)

(*b*) When seam welding extends for the full distance between abrupt changes in the direction of the welding (see Article 310), no length dimension need be shown on the welding symbol.

(*c*) When seam welding extends less than the distance between abrupt changes in the direction of the welding, or less than the full length of the joint (see Article 310), the extent shall be dimensioned, thus: (See also Fig. 36*C*.)



1004. Dimensioning of Intermittent Seam Welding

(*a*) The pitch (center-to-center spacing) of intermittent seam welding shall be shown as the distance between centers of the weld increments.

(*b*) The pitch (center-to-center spacing) of intermittent seam welding shall be shown to the right of the length dimension, thus: (See also Fig. 36*A*.)

1005. Termination of Intermittent Seam Welding

(*a*) When intermittent seam welding is used by itself, the symbol indicates that increments shall be located at the ends of the dimensioned length. (See Fig. 36*A*.)

(*b*) When intermittent seam welding is used between continuous seam welding, the symbol indicates that spaces equal to the pitch minus the length of one increment shall be left at the ends of the dimensioned length.

1006. Combination of Intermittent and Continuous Seam Welding

Separate symbols shall be used for intermittent and continuous seam welding when the two are used in combination.

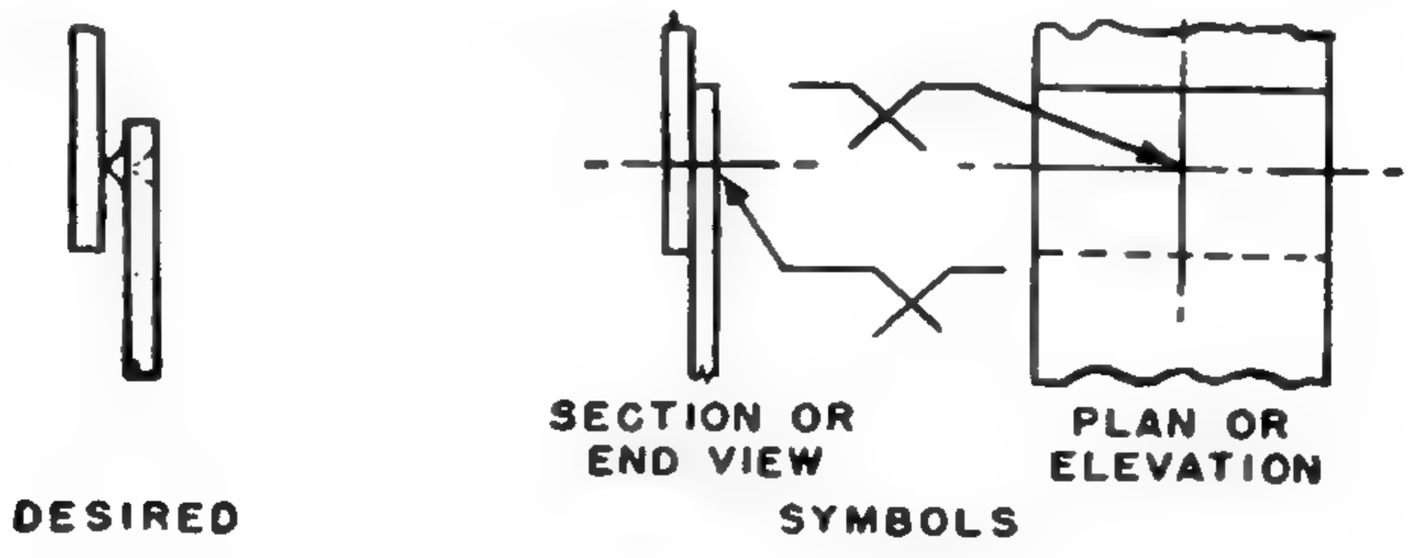
1007. Flush Seam-Welded Joints

When the exposed surface of one member of a seam-welded joint is to be flush, that surface shall be indicated by adding the flush-contour symbol to the weld symbol, observing the usual location significance, thus:

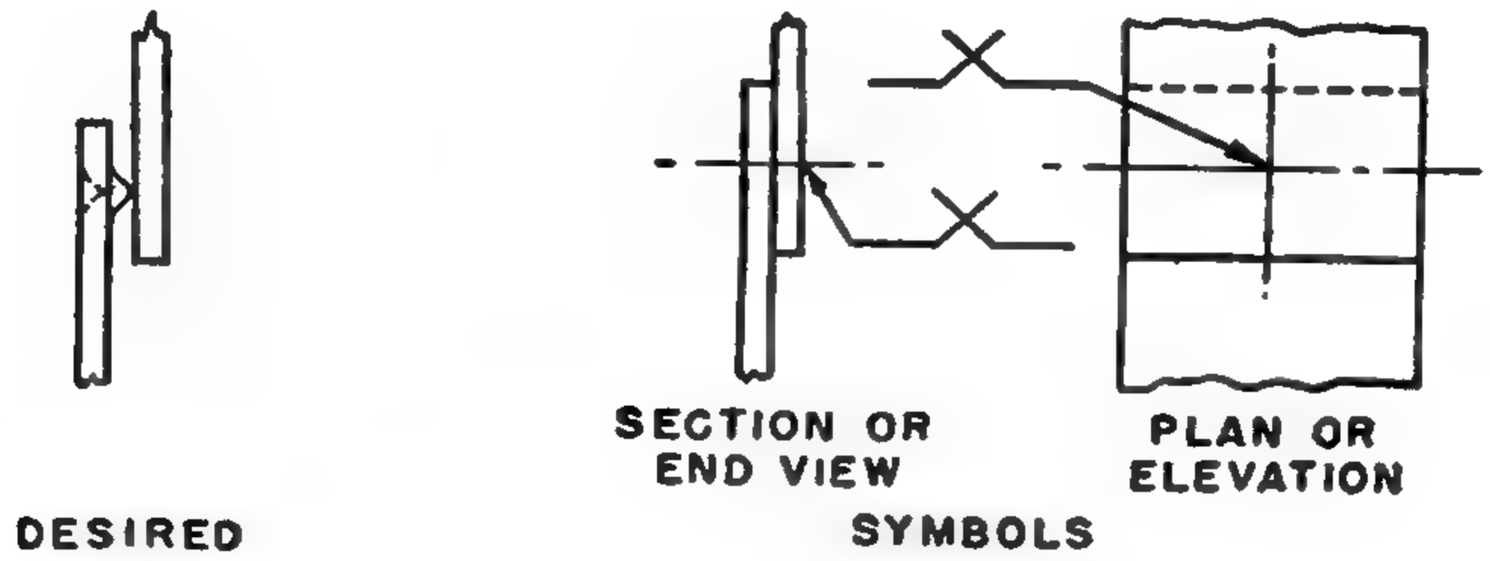
SECTION XI—PROJECTION WELDS

1101. General

(*a*) Embossments on the arrow-side member of a joint for projection welding shall be indicated by placing the weld symbol on the side of the reference line toward the reader, thus: (See also Fig. 18*A*.)



(*b*) Embossments on the other-side member of a joint for projection welding shall be indicated by placing the weld symbol on the side of the reference line away from the reader, thus: (See also Fig. 18*B*.)



(*c*) Proportions of projections shall be shown by a detail or other suitable means.

(*d*) Dimensions of projection welds shall be shown on the same side of the reference line as the weld symbol, thus: (See also Fig. 38*C*.)

1102. Size of Projection Welds

Projection welds shall be dimensioned by either size or strength, as follows:

(1) The size of projection welds shall be designated as the diameter of the weld expressed decimally in hundredths of an inch, and shall be shown, with inch marks, to the left of the weld symbol, thus: (See also Fig. 37*A*.)

(2) The strength of projection welds shall be designated as the minimum acceptable shear strength in pounds per weld, and shall be shown to the left of the weld symbol, thus: (See also Fig. 37*B*.)

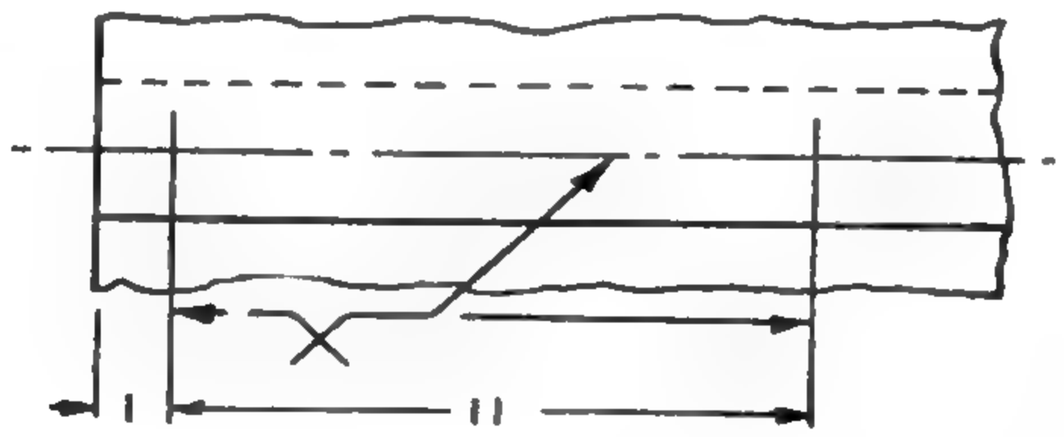
1103. Spacing of Projection Welds

The pitch (center-to-center spacing) of projection welds shall be shown

to the right of the weld symbol, thus: (See also Fig. 37*C*.)

1104. Extent of Projection Welding

When projection welding extends less than the distance between abrupt changes in the direction of the welding, or less than the full length of the joint (see Article 310), the extent shall be dimensioned, thus: (See also Fig. 38*A*.)



1105. Number of Projection Welds

When a definite number of projection welds is desired in a certain joint, the number shall be shown in parentheses, thus: (See also Fig. 38*B*.)

1106. Flush Projection-Welded Joints

When the exposed surface of one member of a projection welded joint is to be made flush, that surface shall be indicated by adding the flush-contour symbol to the weld symbol, observing the usual location significance, thus:

SECTION XII—FLASH AND UPSET WELDS

1201. General

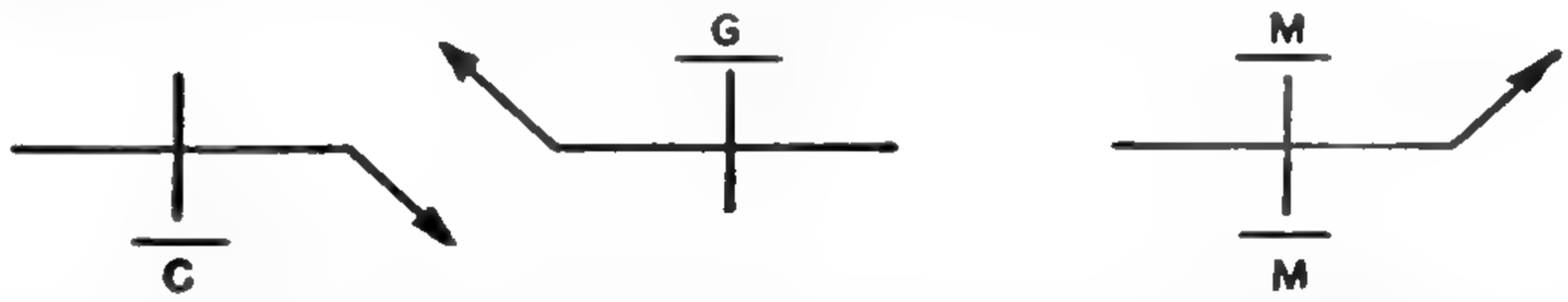
(*a*) Flash and upset weld symbols have no arrow-side or other-side

significance in themselves although supplementary symbols used in conjunction therewith may have such significance (see Article 1202). Flash or upset weld symbols shall be centered in the reference line. (See Fig. 19.)

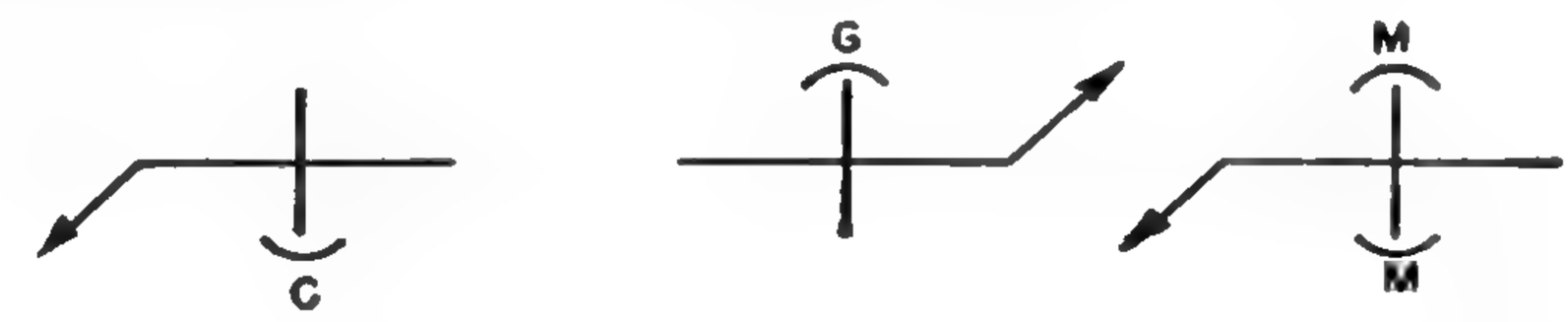
(*b*) Dimensions of flash and upset welds shall not be shown on the welding symbol.

1202. Surface Contour of Flash and Upset Welds

(*a*) Flash and upset welds that are to be made flush by mechanical means shall be shown by adding both the flush-contour symbol and the user's standard finish symbol* to the weld symbol, observing the usual location significance, thus: (See also Fig. 39*A*.)



(*b*) Flash and upset welds that are to be mechanically finished to a convex contour shall be shown by adding both the convex-contour symbol and the user's standard finish symbol* to the weld symbol, observing the usual location significance, thus: (See also Fig. 39*B*.)



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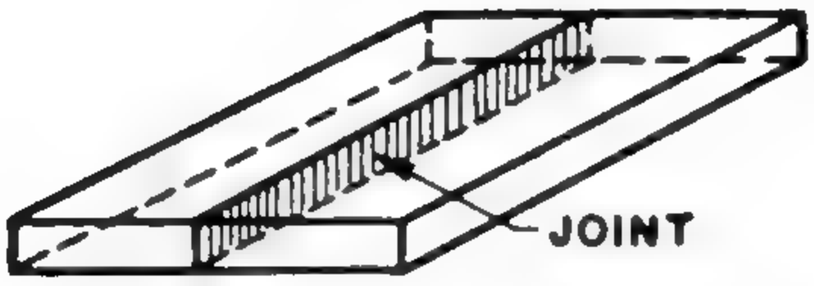
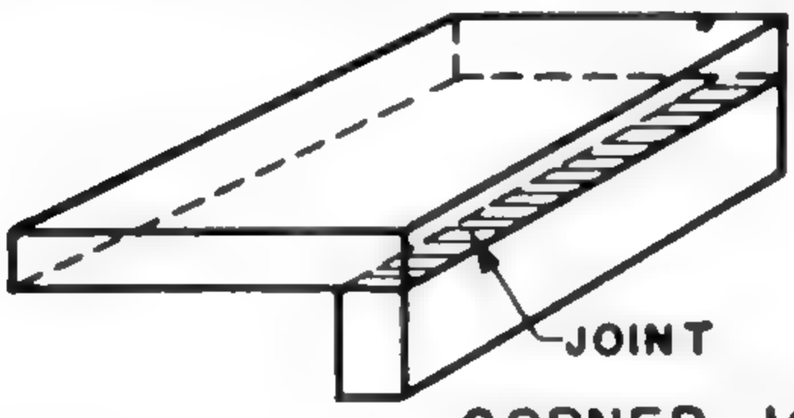
* Finish symbols used herein indicate the method of finishing ("*C*" = chipping; "*G*" = grinding; "*M*" = machining) and not the degree of finish.



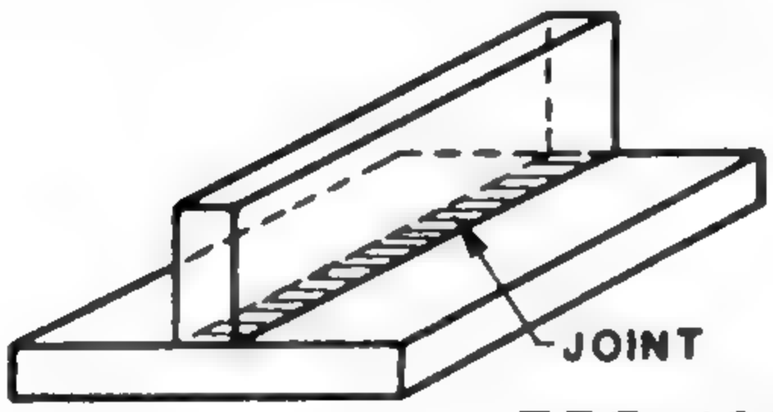
APPLICABLE WELDS
SQUARE-GROOVE
V-GROOVE
BEVEL-GROOVE
U-GROOVE
J-GROOVE
FLASH
UPSET

(A) BUTT JOINT



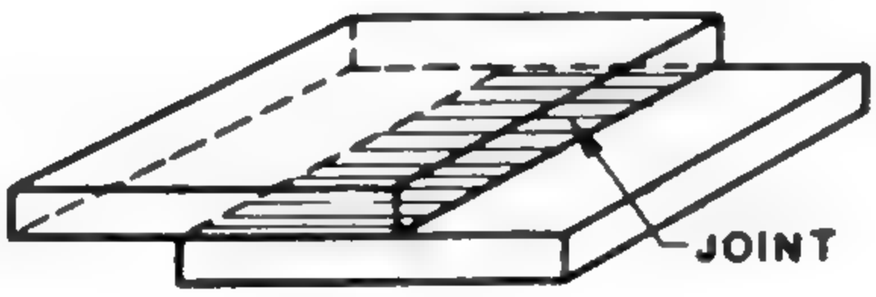
APPLICABLE WELDS
SQUARE-GROOVE
V-GROOVE
BEVEL-GROOVE
U-GROOVE
J-GROOVE
FILLET
FLASH

(B) CORNER JOINT



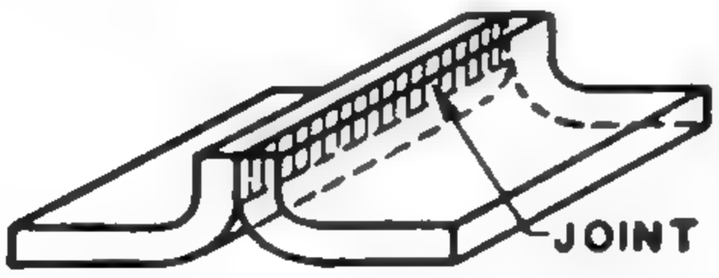
APPLICABLE WELDS
BEVEL-GROOVE
J-GROOVE
FILLET
SLOT
PLUG

(C) TEE JOINT



APPLICABLE WELDS
FILLET
BEVEL-GROOVE
J-GROOVE
SLOT
PLUG
SPOT
PROJECTION
SEAM

(D) LAP JOINT



APPLICABLE WELDS
SQUARE-GROOVE
BEVEL-GROOVE
V-GROOVE
U-GROOVE
J-GROOVE
SPOT
SEAM
PROJECTION

(E) EDGE JOINT

Fig. 5—Basic Types of Joints

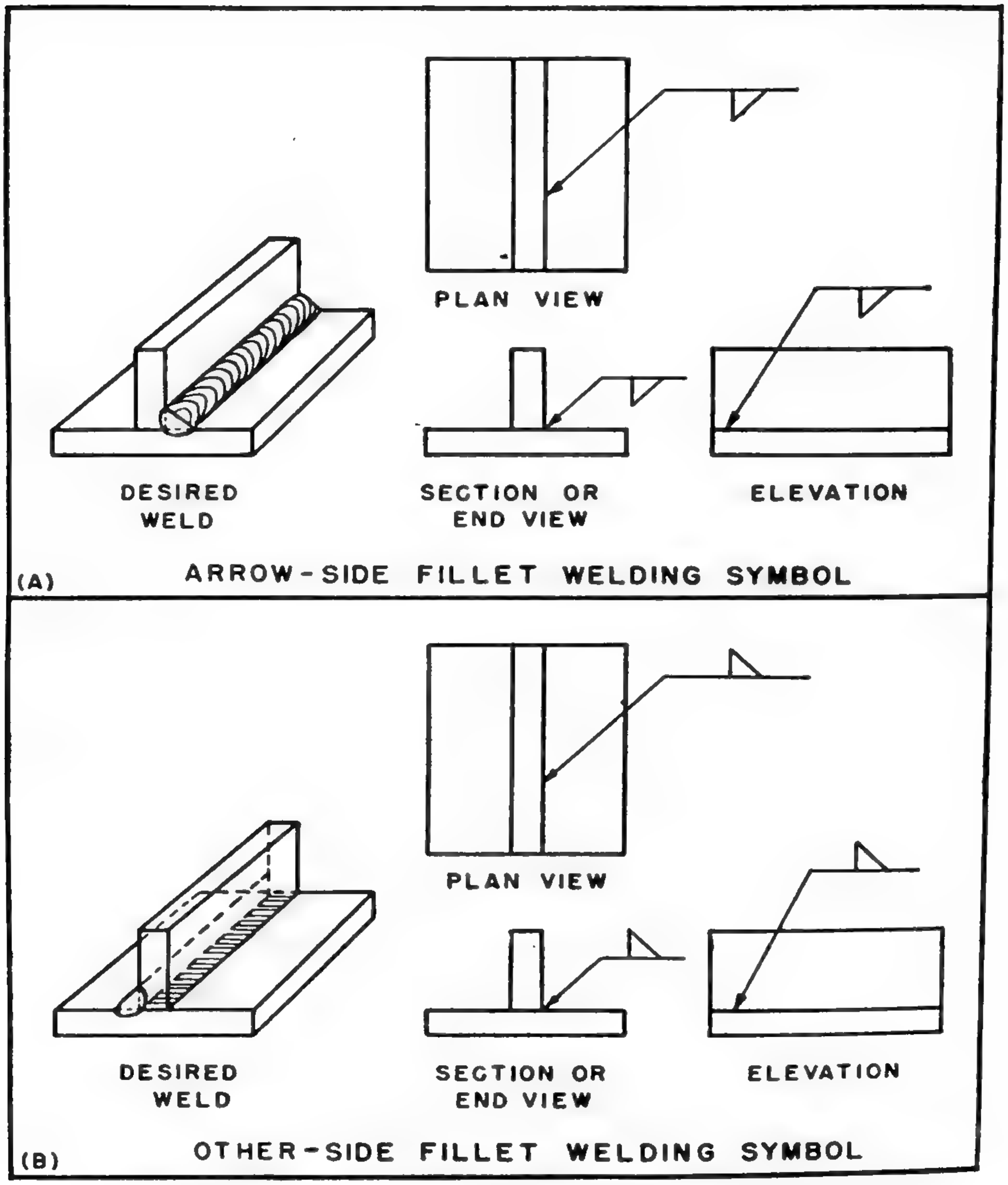


Fig. 6—Application of Fillet Welding Symbols

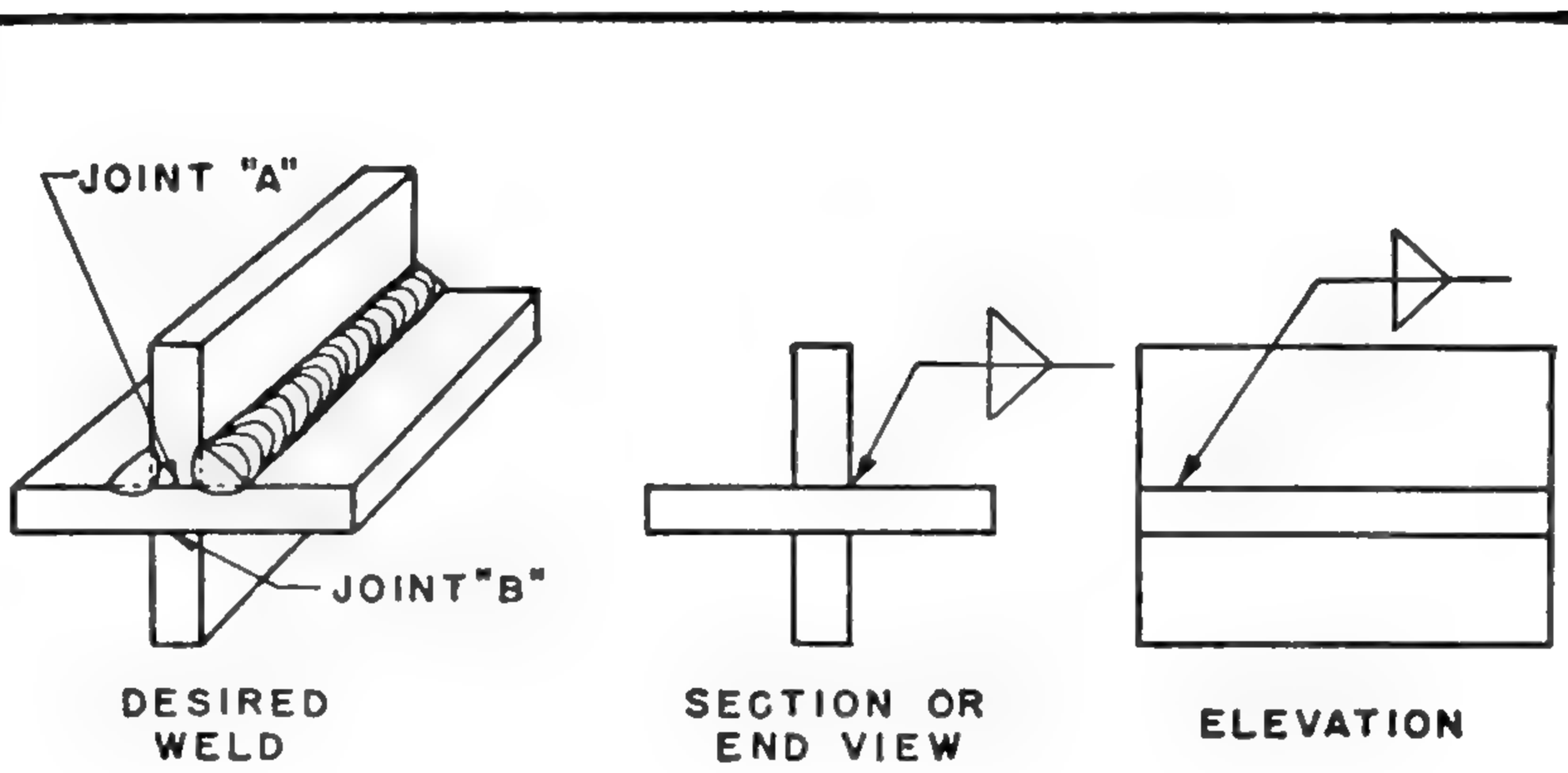


Fig. 7—Application of Fillet Welding Symbols

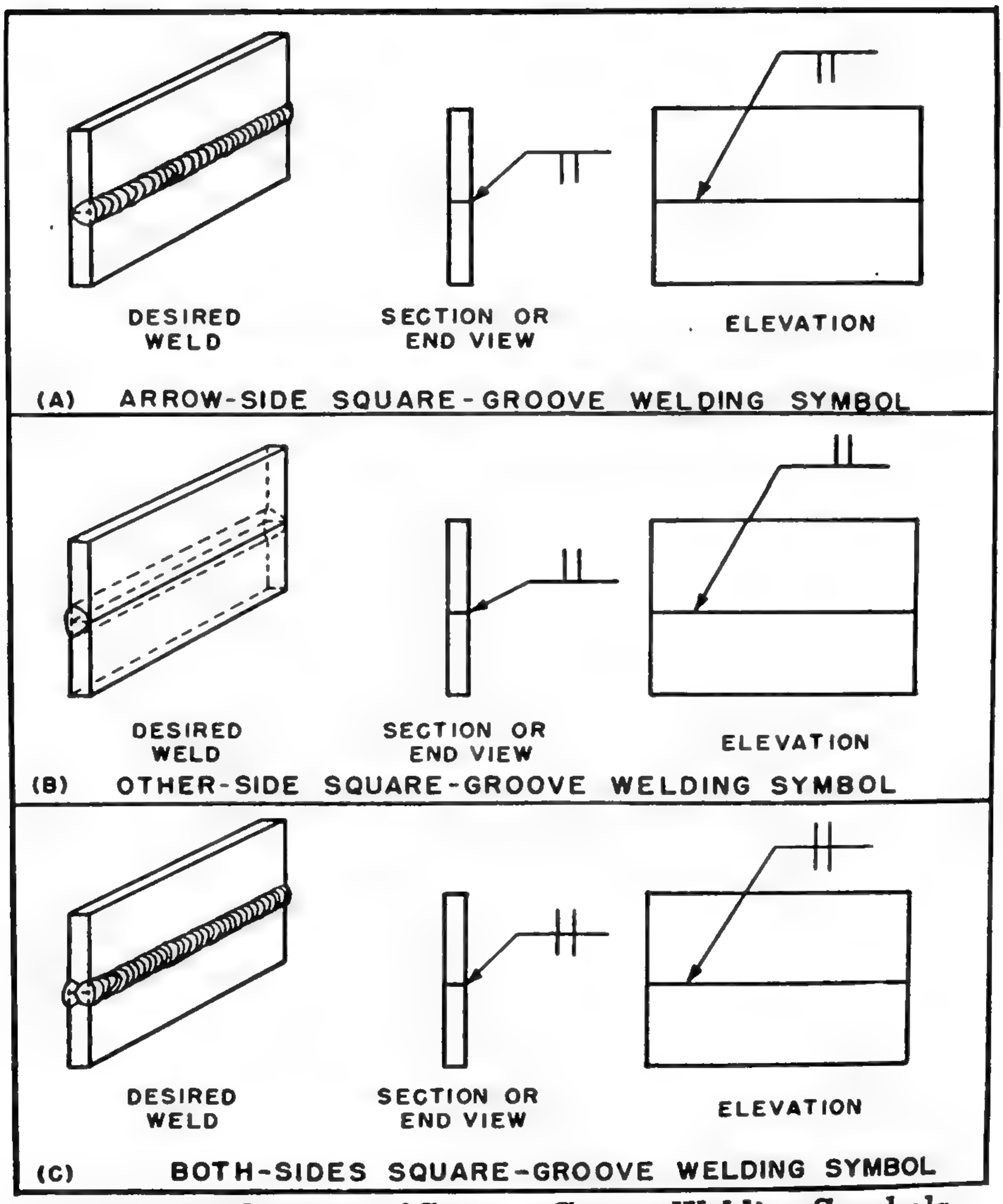


Fig. 8—Application of Square-Groove Welding Symbols

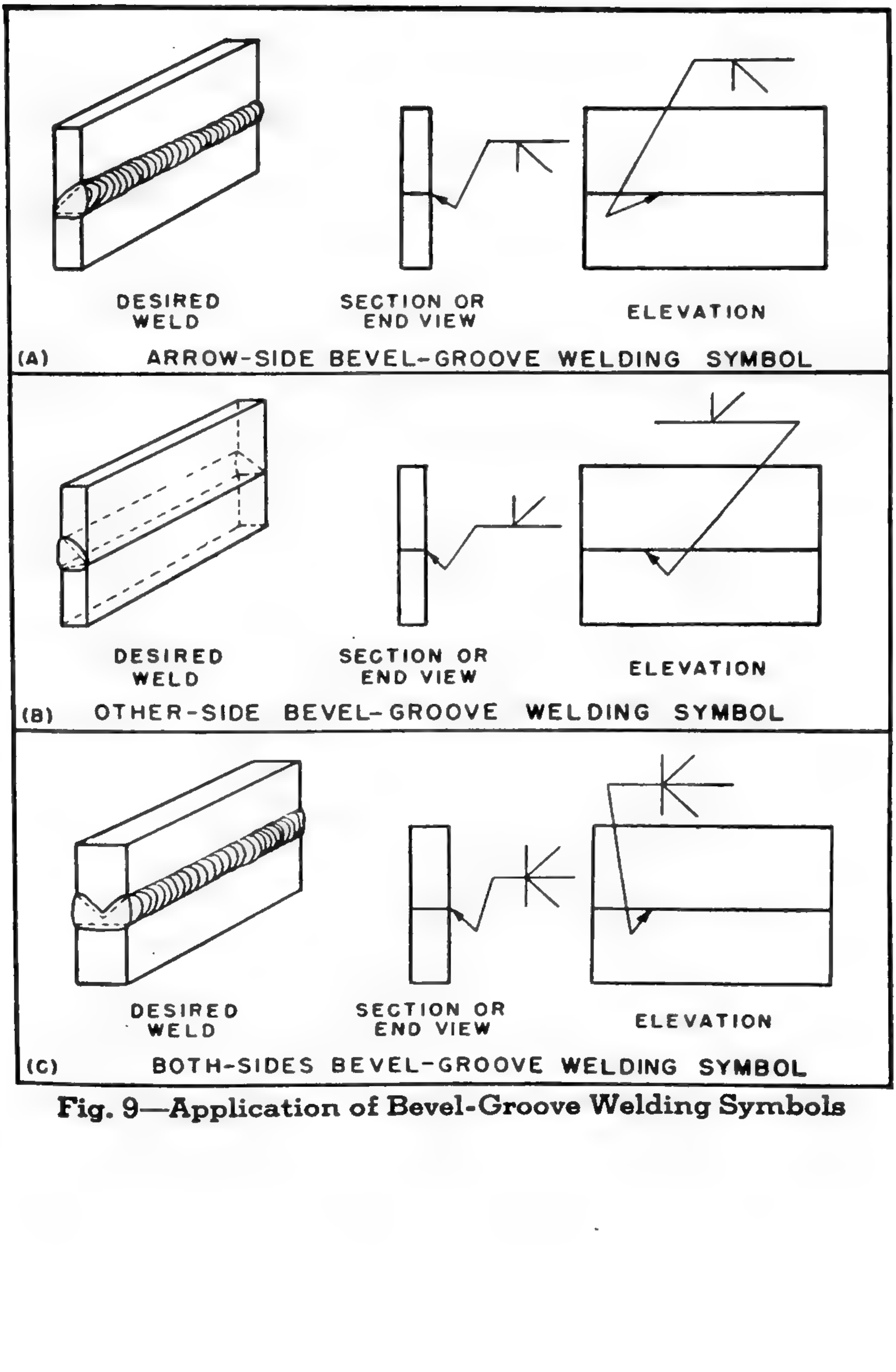


Fig. 9—Application of Bevel-Groove Welding Symbols

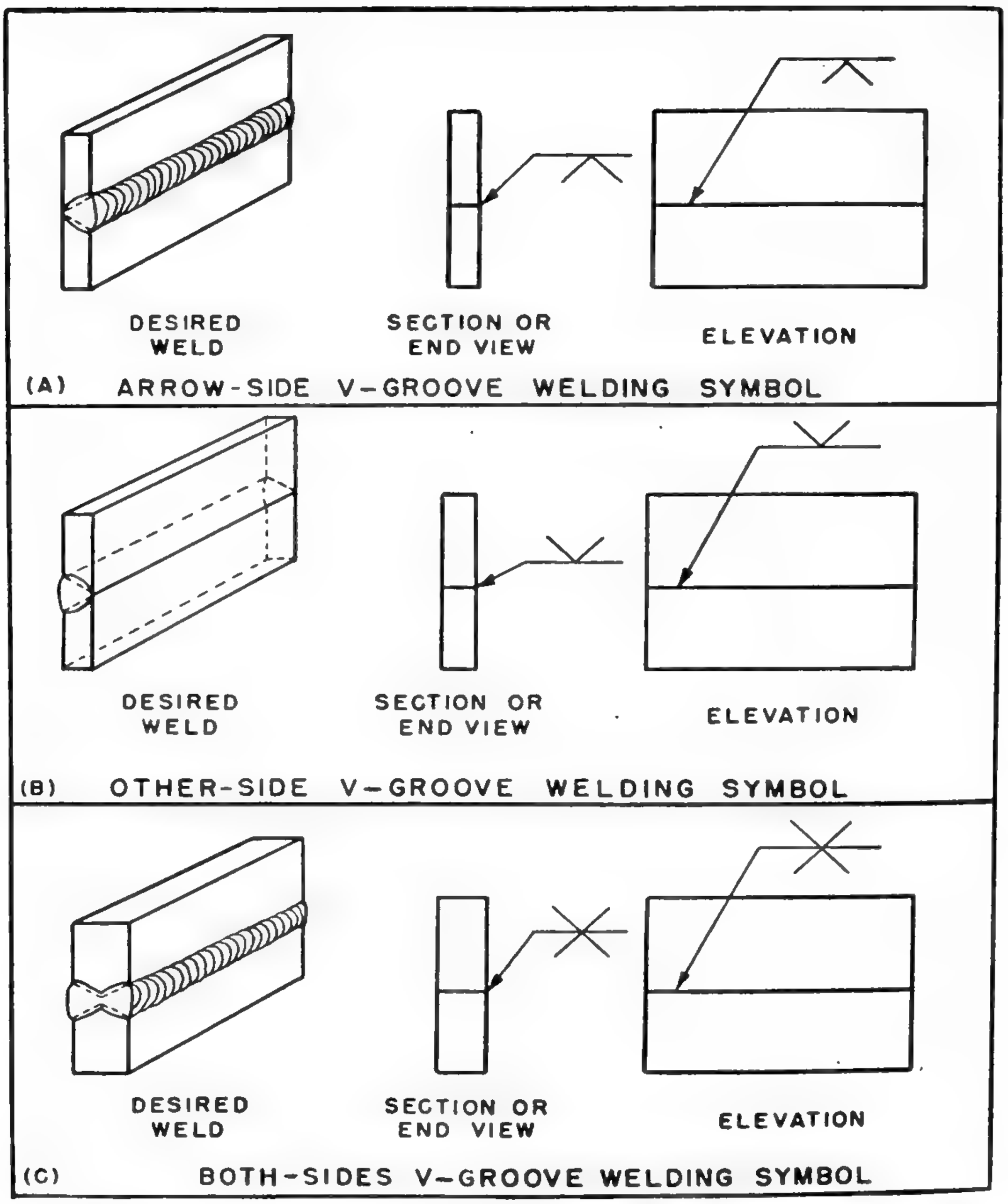


Fig. 10—Application of V-Groove Welding Symbols

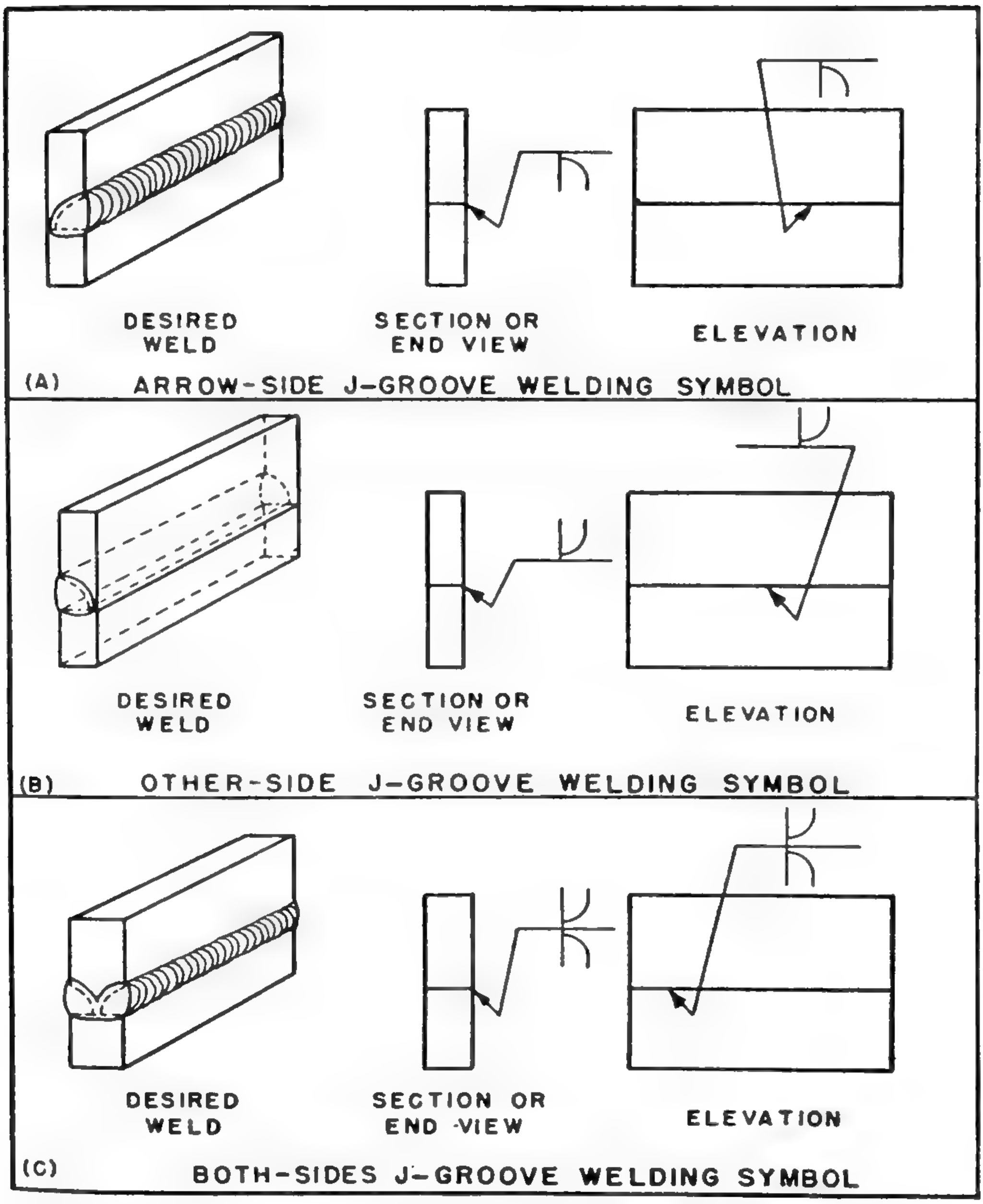


Fig. 11—Application of J-Groove Welding Symbols

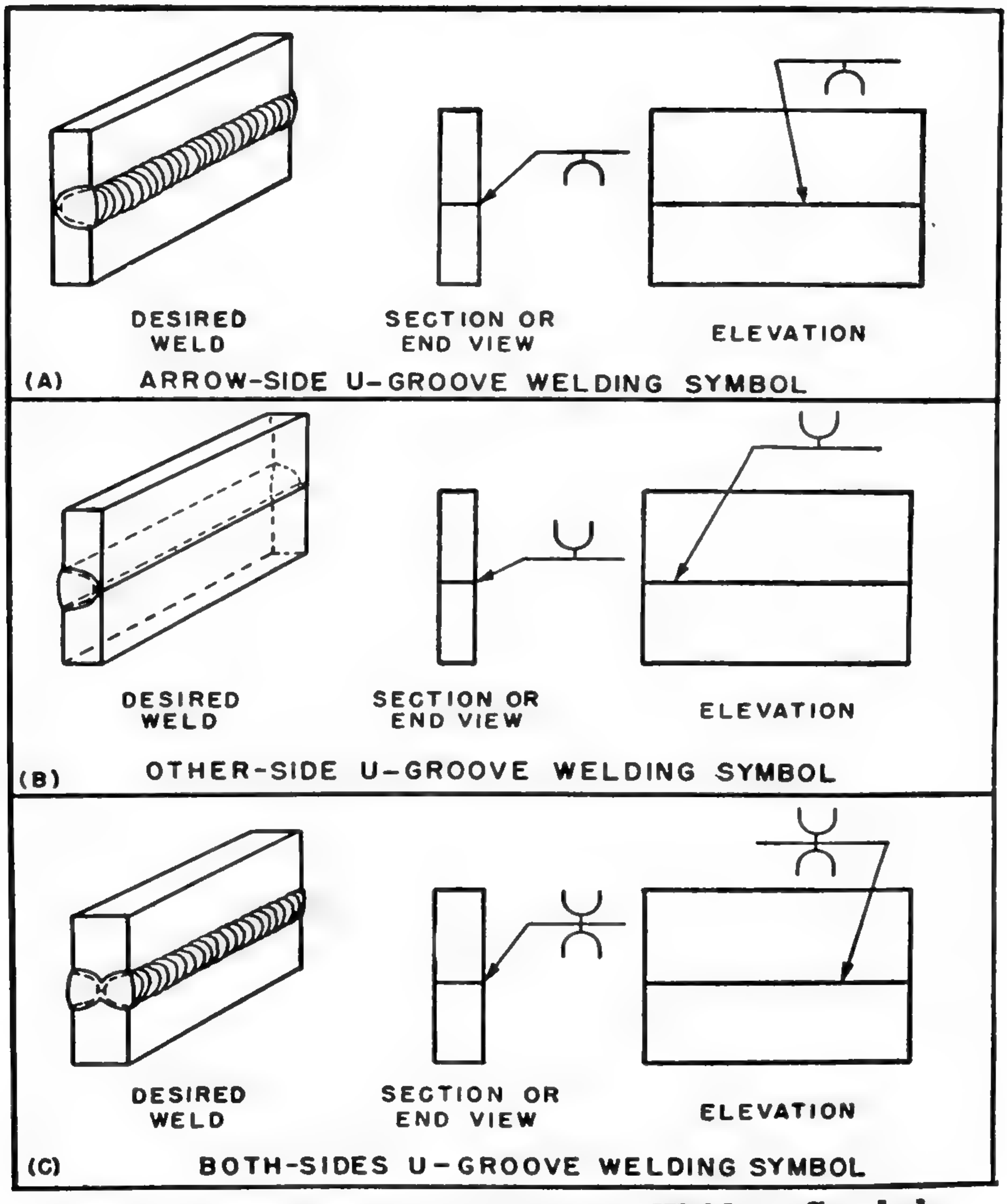
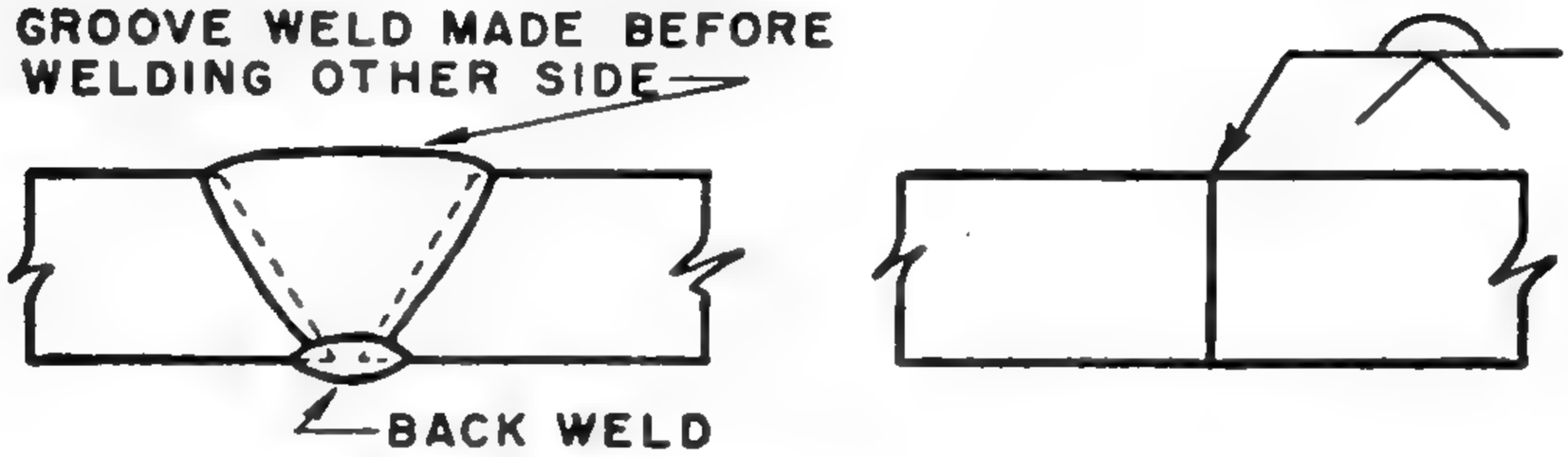
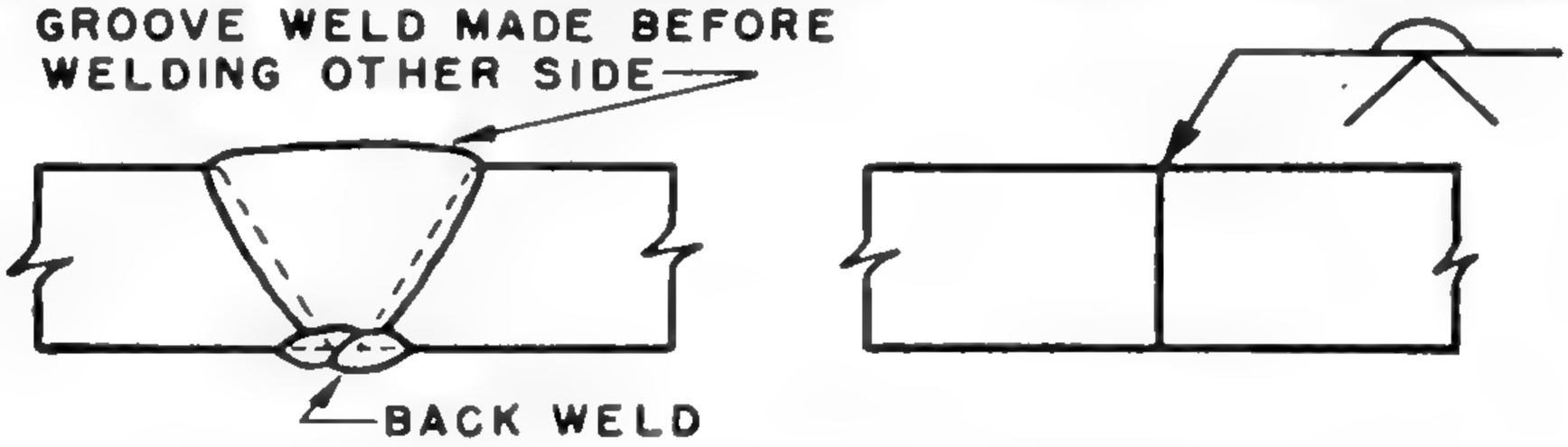


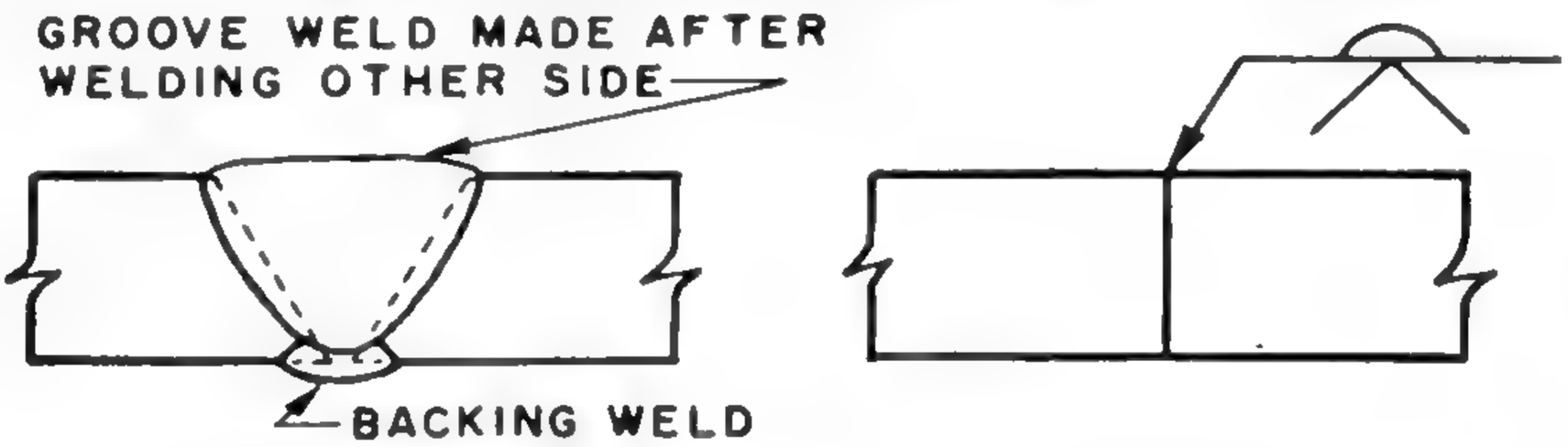
Fig. 12—Application of U-Groove Welding Symbols



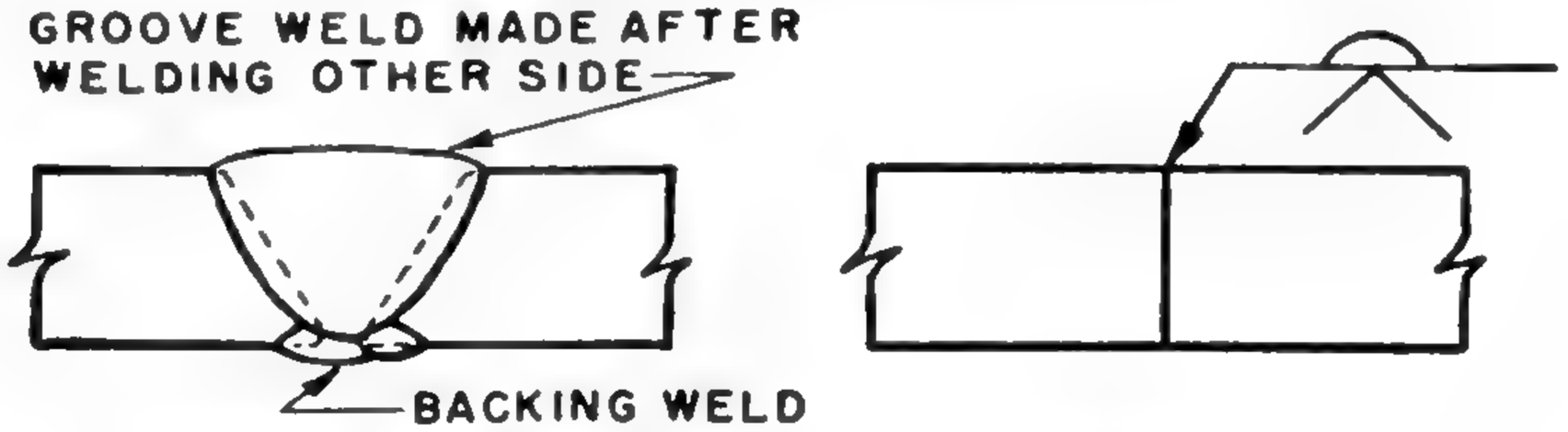
(A) USE OF BEAD WELD SYMBOL TO INDICATE SINGLE-PASS BACK WELD



(B) USE OF BEAD WELD SYMBOL TO INDICATE MULTIPLE-PASS BACK WELD



(C) USE OF BEAD WELD SYMBOL TO INDICATE SINGLE-PASS BACKING WELD



(D) USE OF BEAD WELD SYMBOL TO INDICATE MULTIPLE-PASS BACKING WELD

Fig. 13—Application of Bead Weld Symbol to Indicate Bead-Type Back and Backing Welds

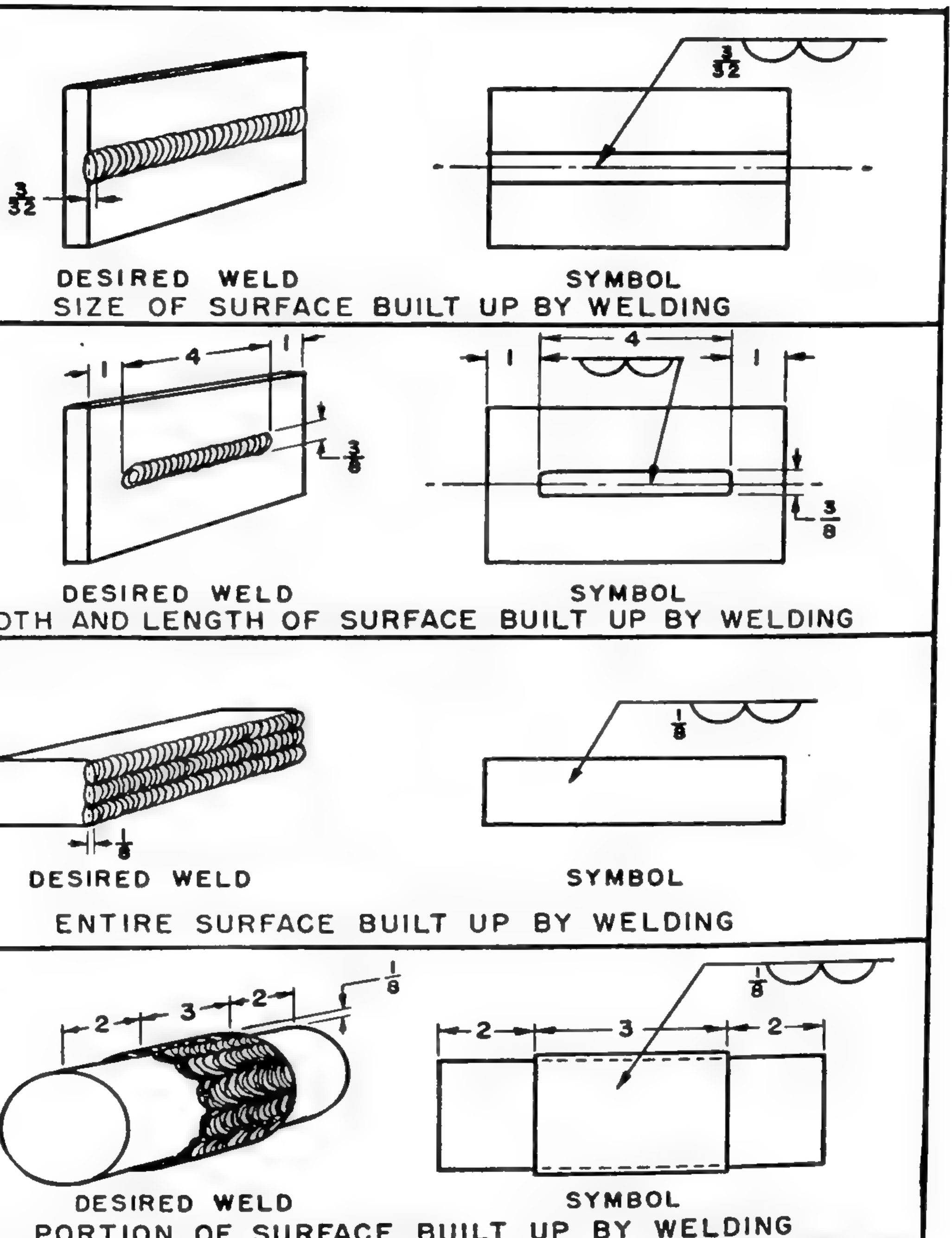


Fig. 14—Application of Dual Bead Weld Symbol to Indicate Surfaces Built Up by Welding

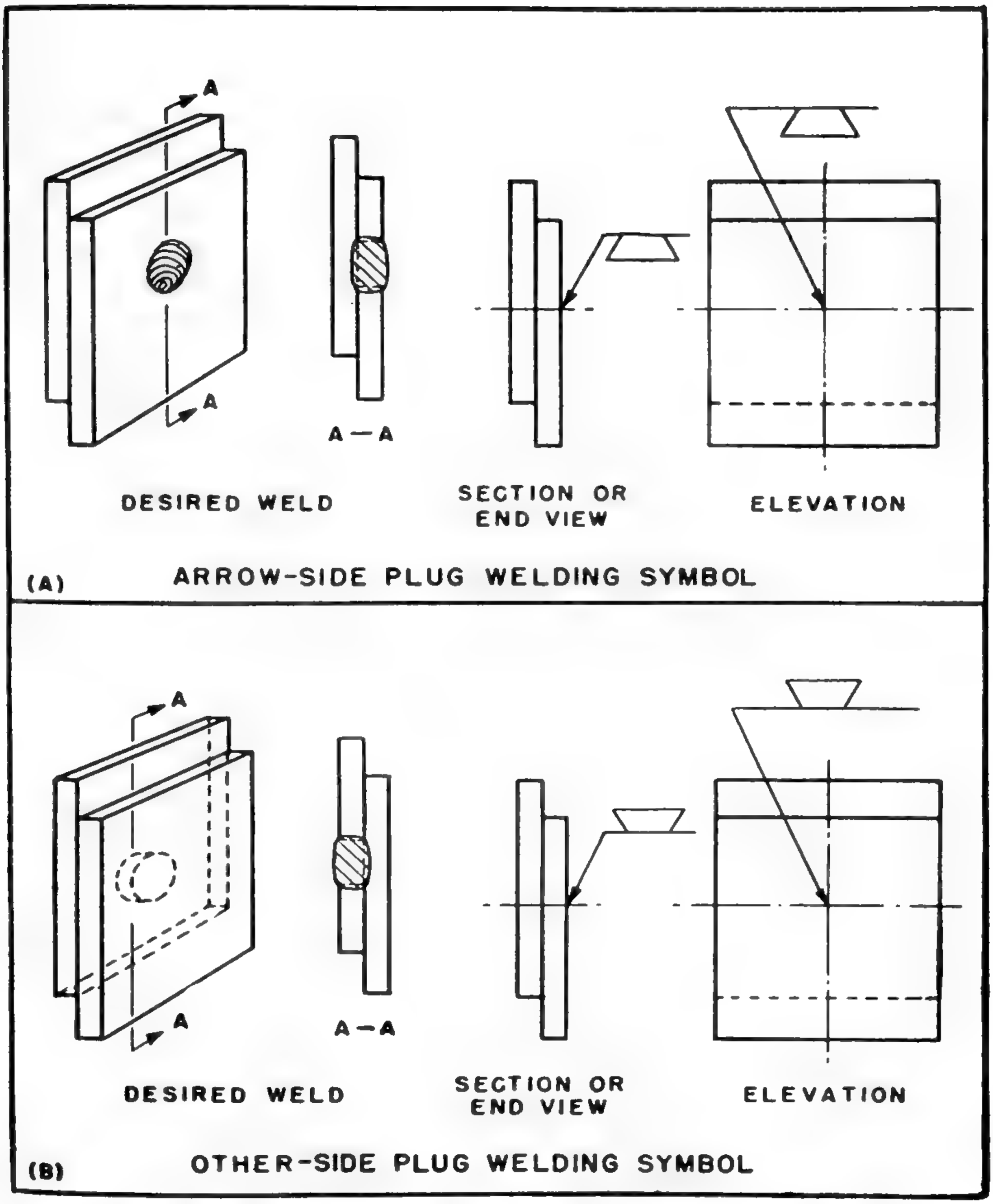
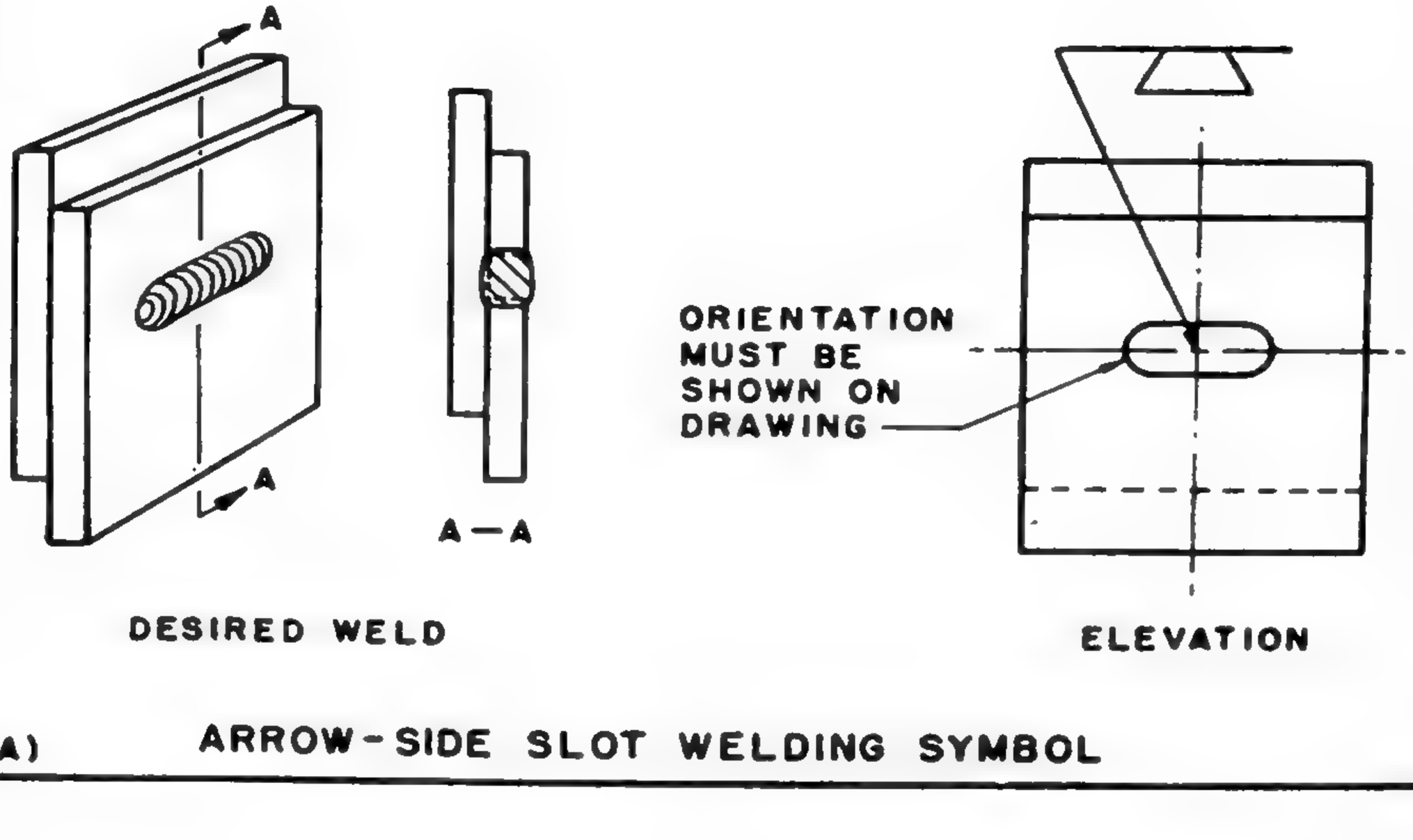
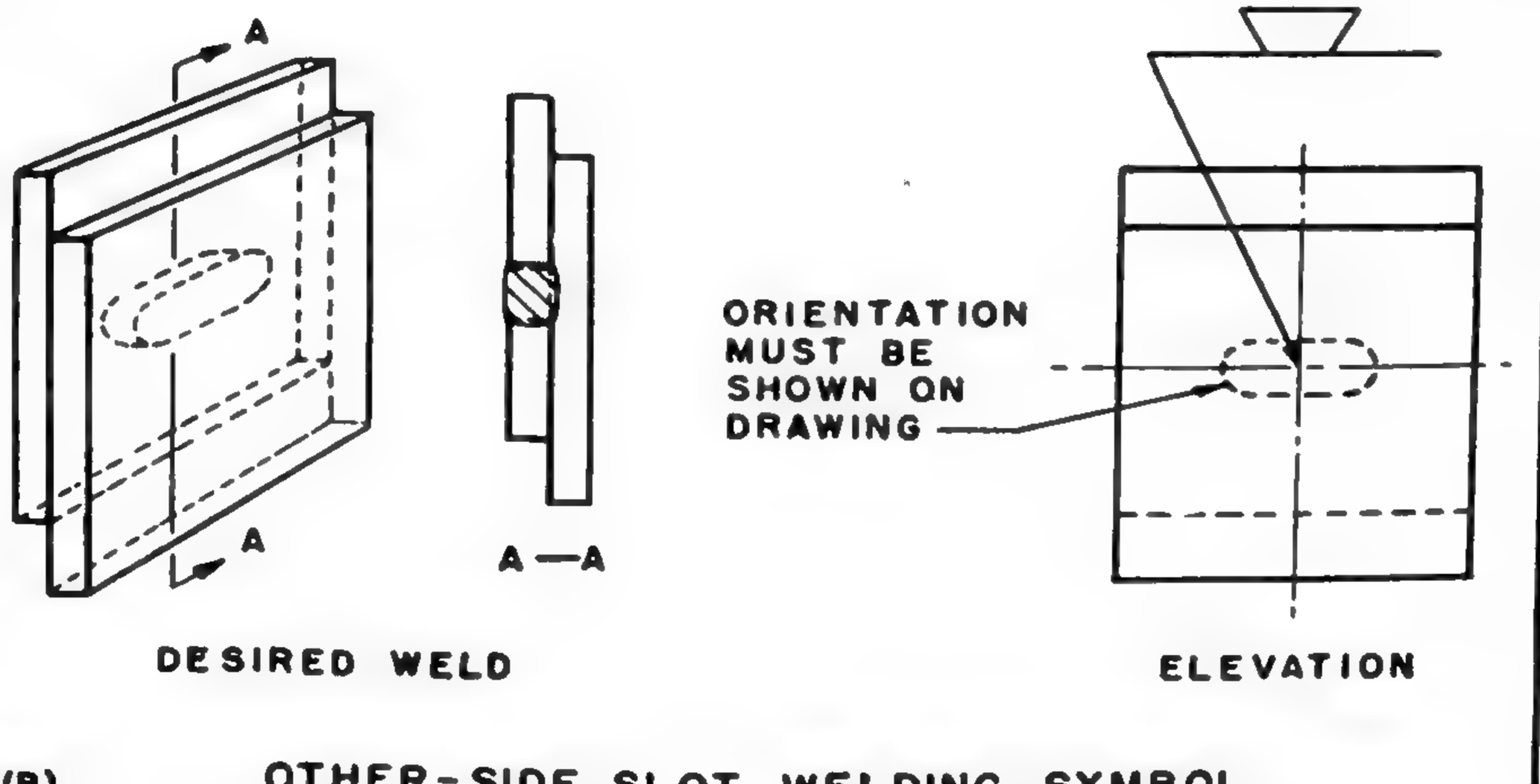


Fig. 15—Application of Plug Welding Symbols

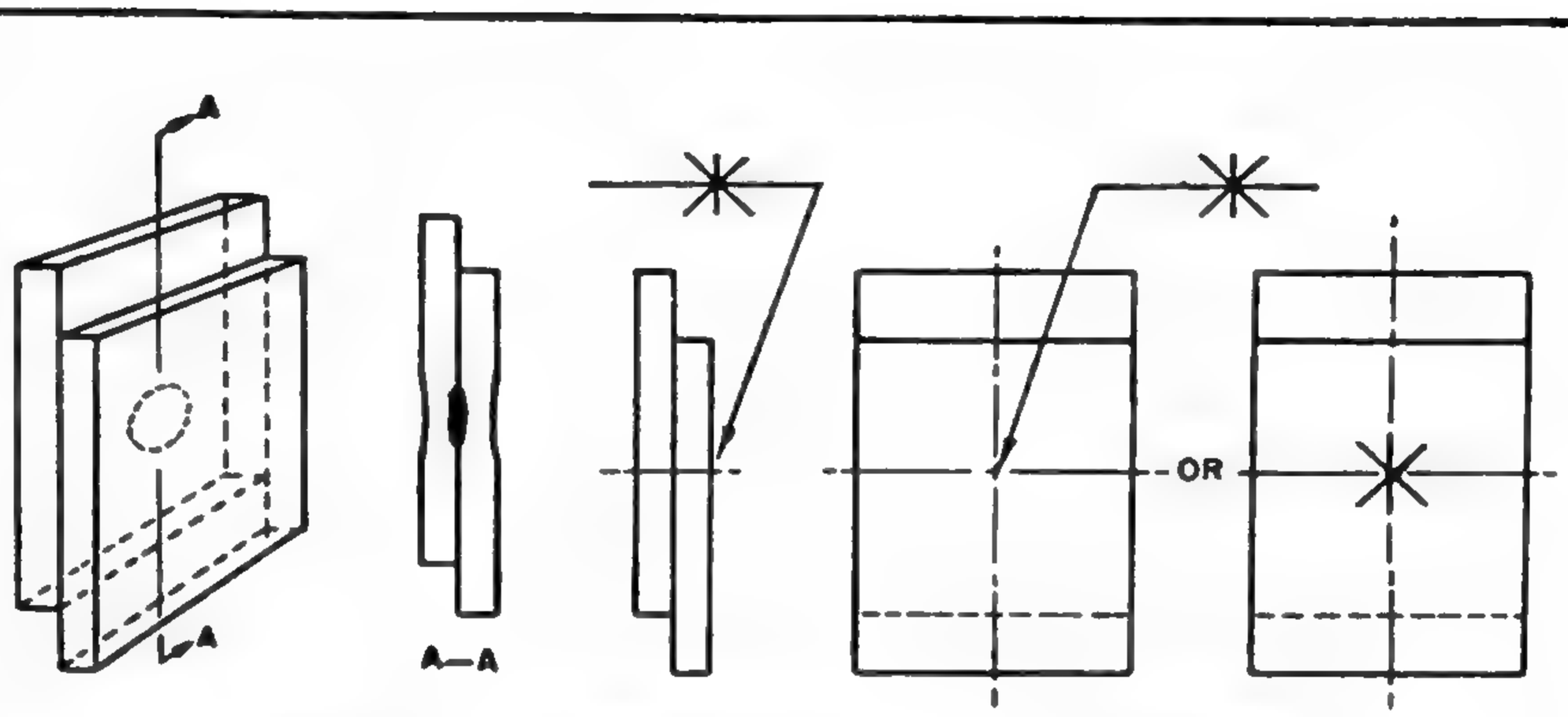


(A) ARROW-SIDE SLOT WELDING SYMBOL

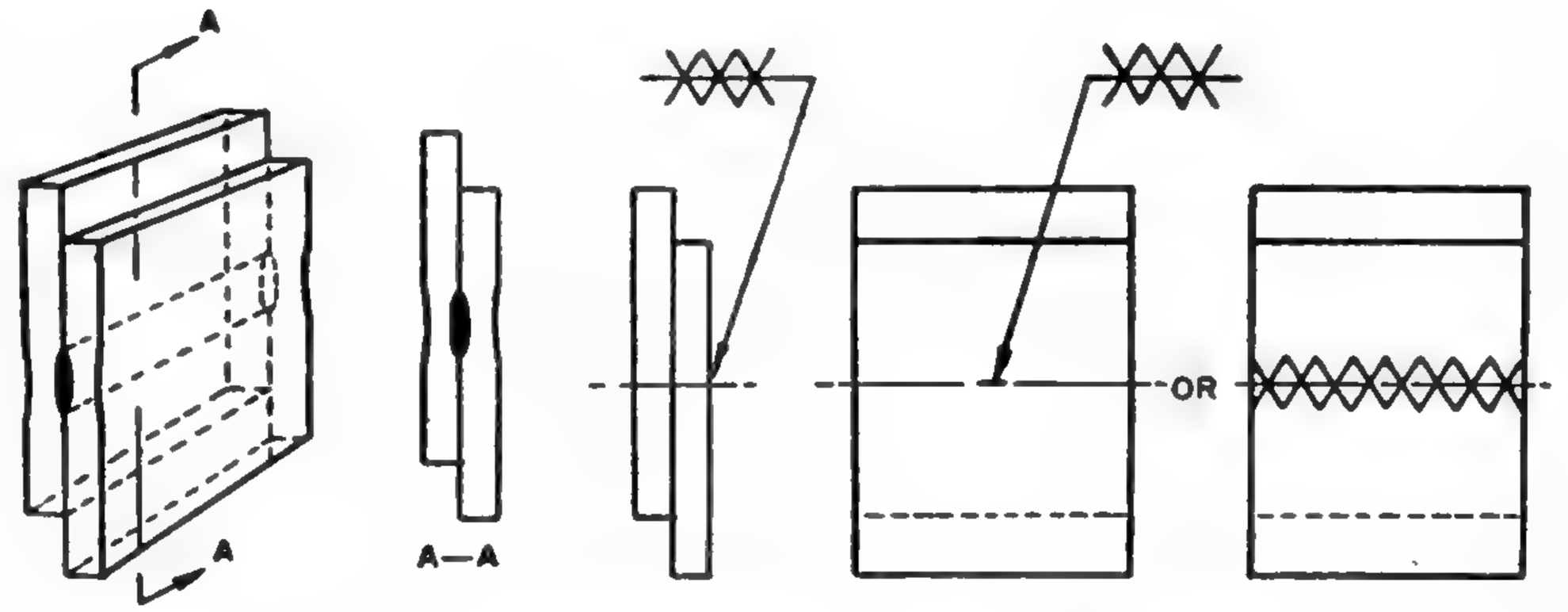


(B) OTHER-SIDE SLOT WELDING SYMBOL

Fig. 16—Application of Slot Welding Symbols



(A) SPOT WELDING SYMBOL (NO ARROW- OR OTHER-SIDE REFERENCE OR SIGNIFICANCE.)



(B) SEAM WELDING SYMBOL (NO ARROW- OR OTHER-SIDE REFERENCE OR SIGNIFICANCE.)

Fig. 17—Application of Spot and Seam Welding Symbols

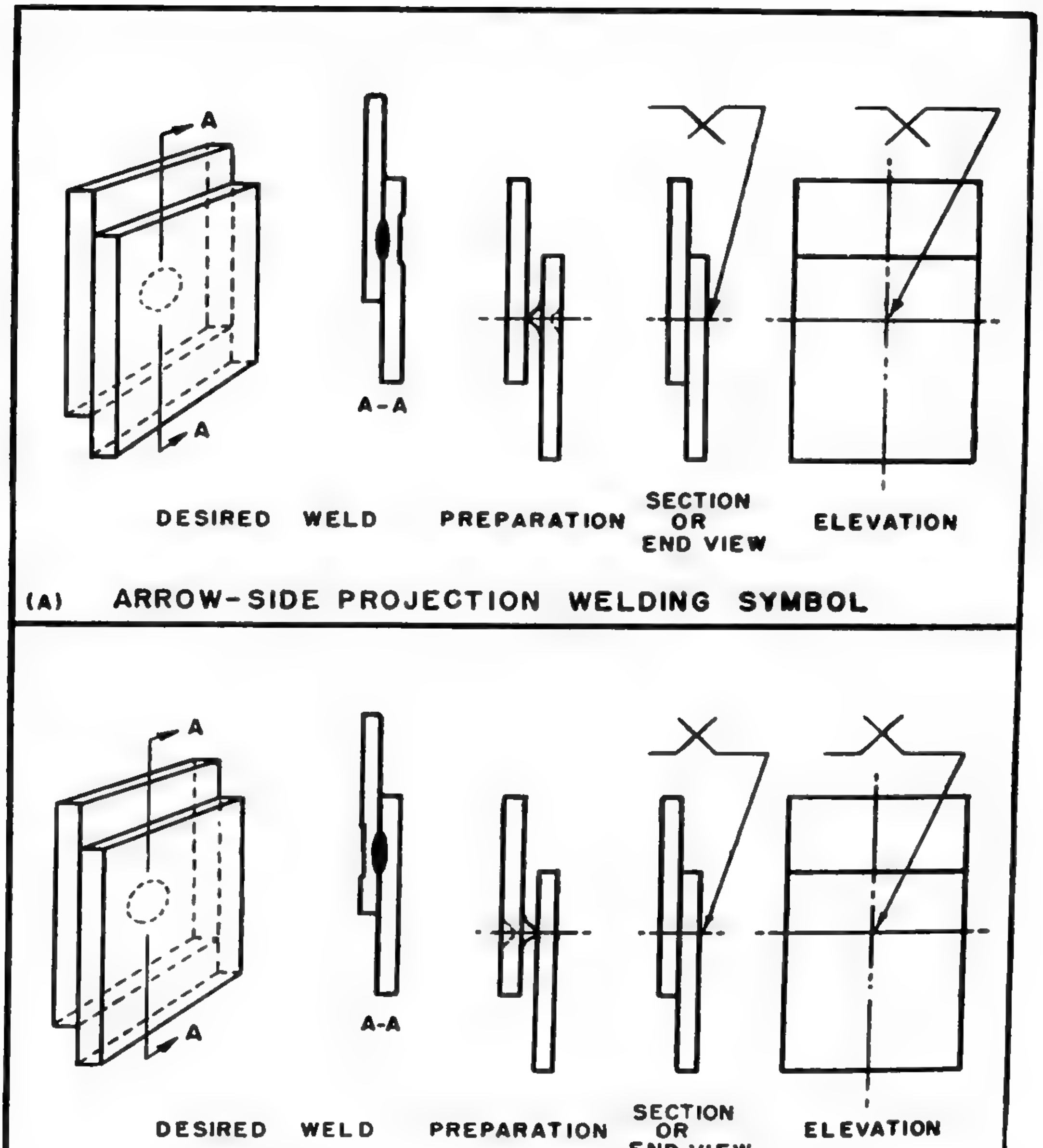
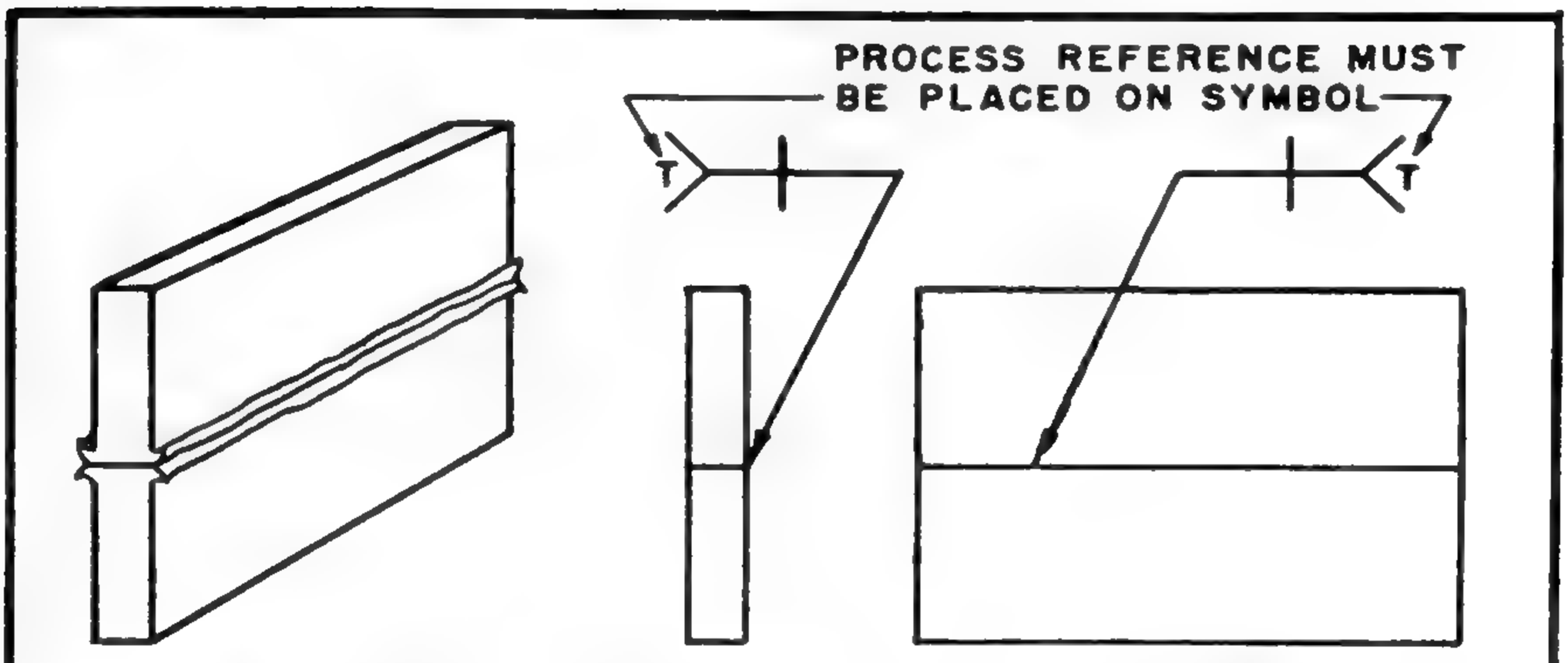
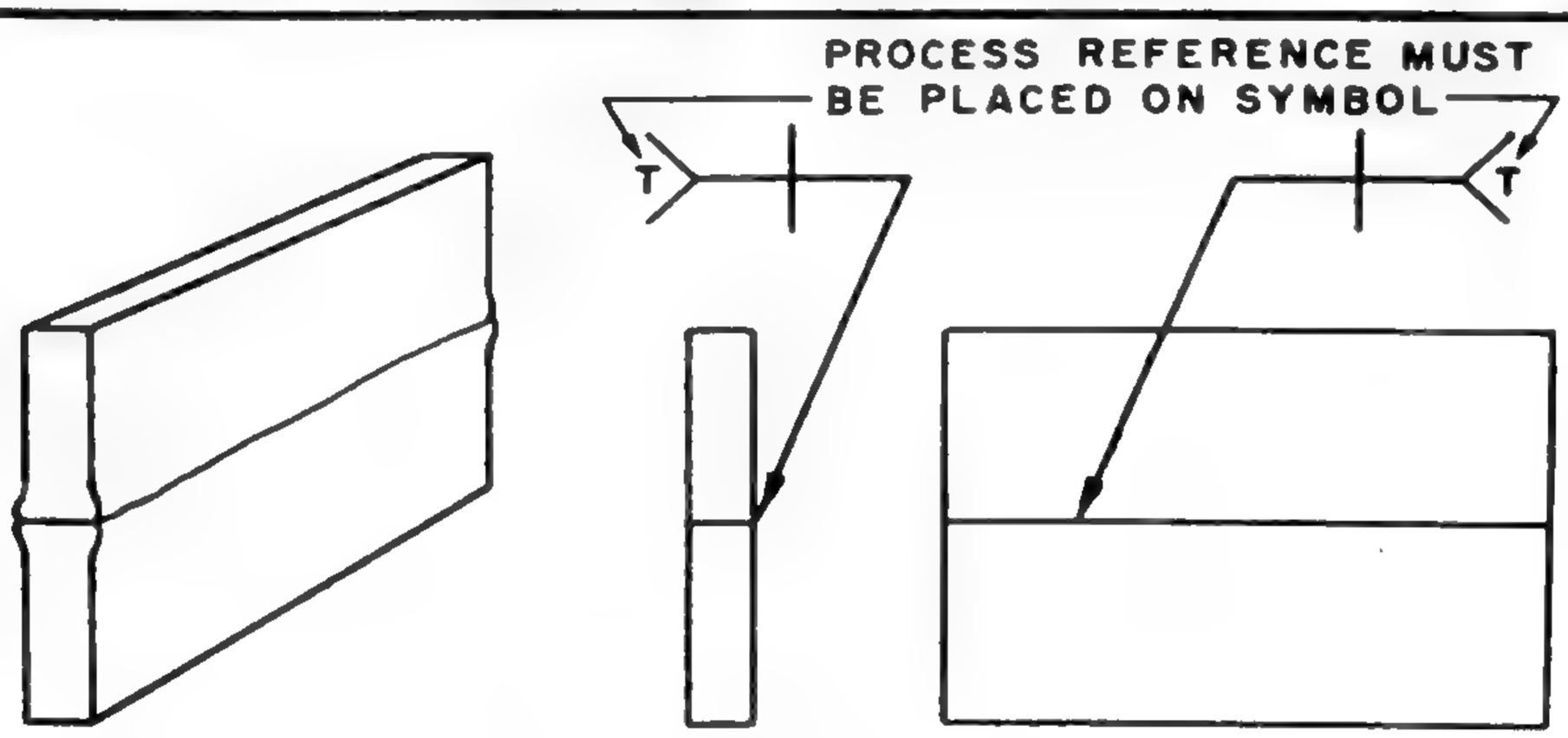


Fig. 18—Application of Projection Welding Symbols



(A) FLASH WELDING SYMBOL (NO ARROW - OR OTHER - SIDE REFERENCE OR SIGNIFICANCE)



(B) UPSET WELDING SYMBOL (NO ARROW - OR OTHER - SIDE REFERENCE OR SIGNIFICANCE.)

Fig. 19—Application of Flash and Upset Welding Symbols

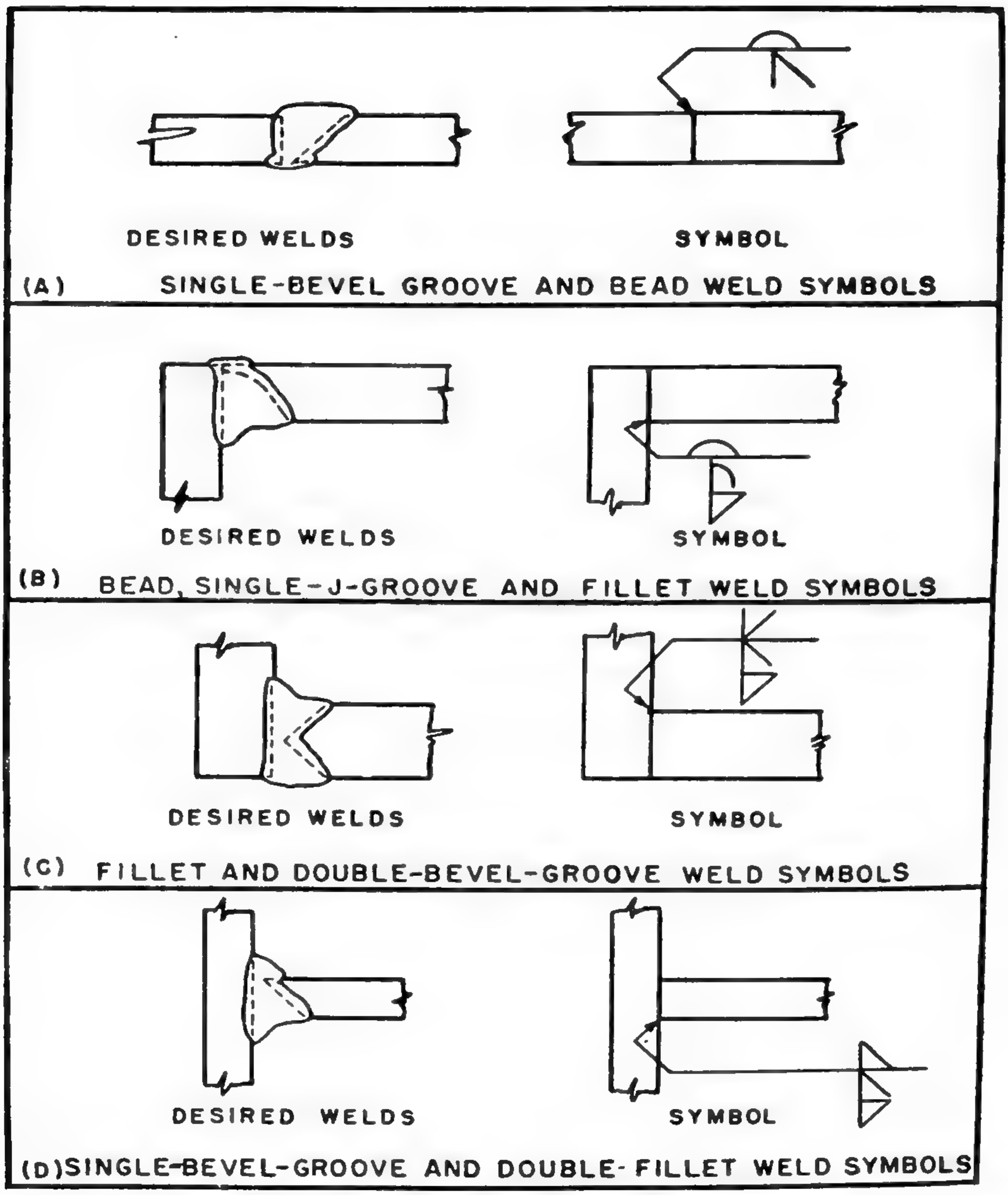


Fig. 20—Combination of Weld Symbols

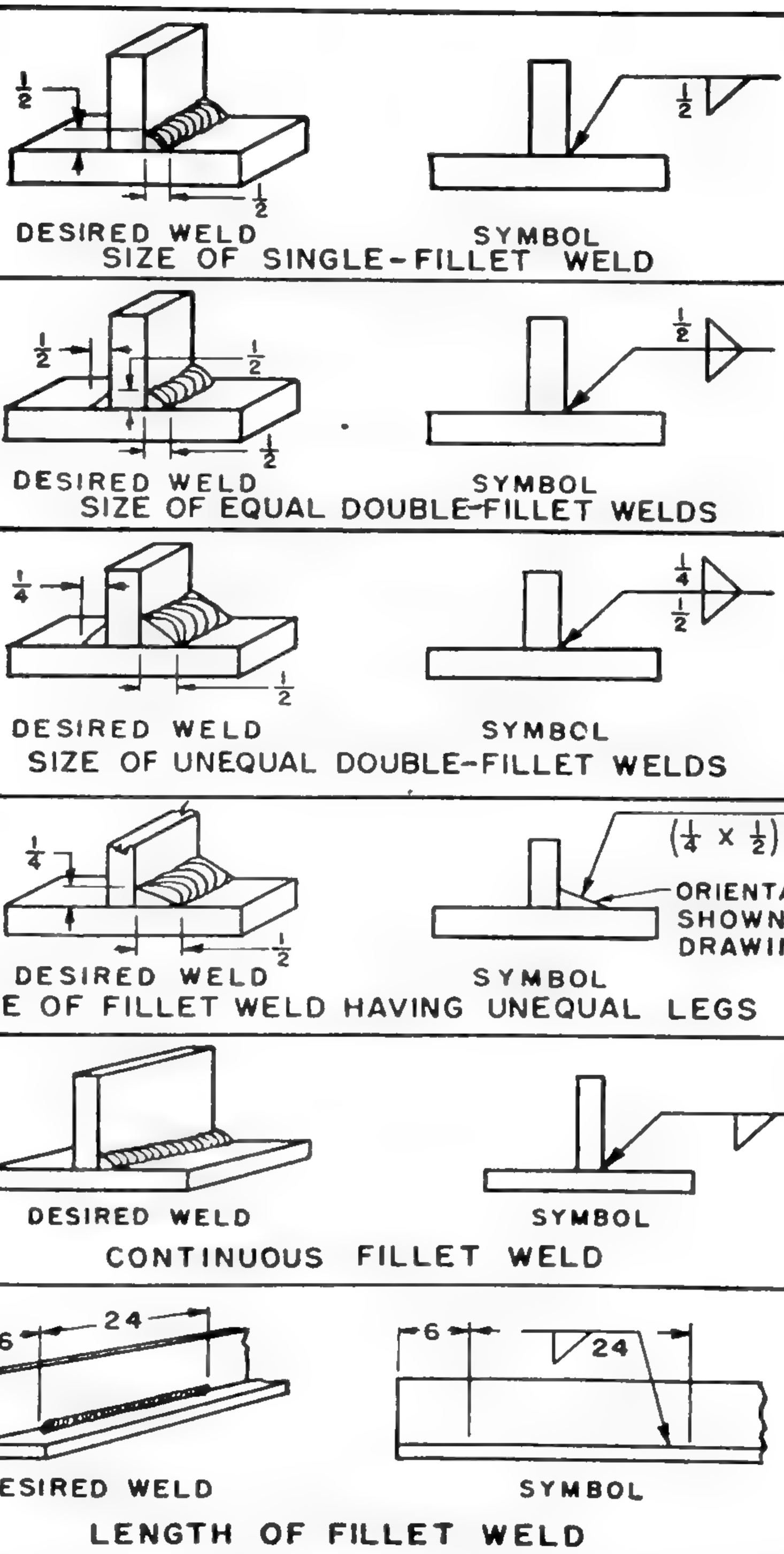


Fig. 21—Application of Dimensions to Fillet Welding Symbols

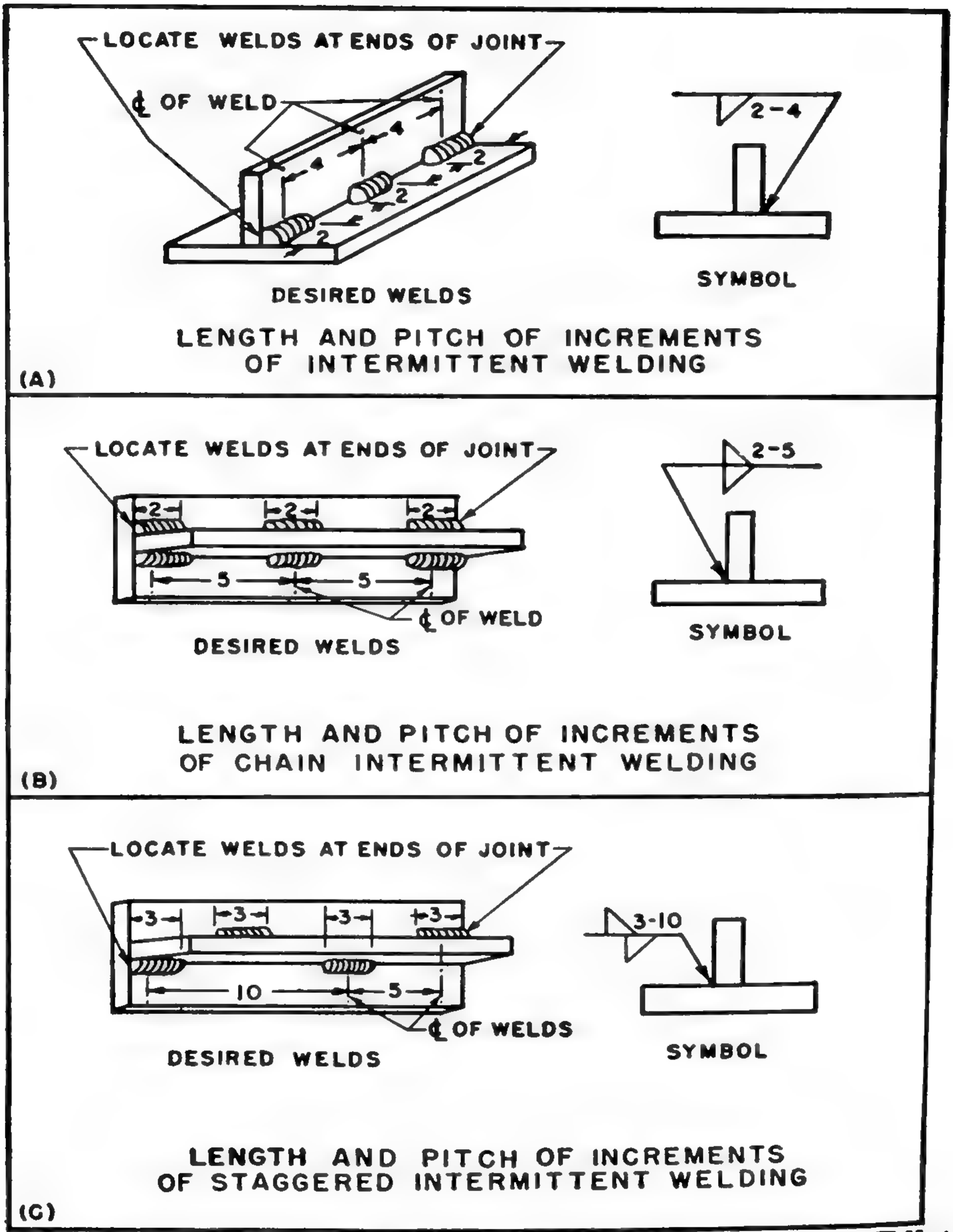
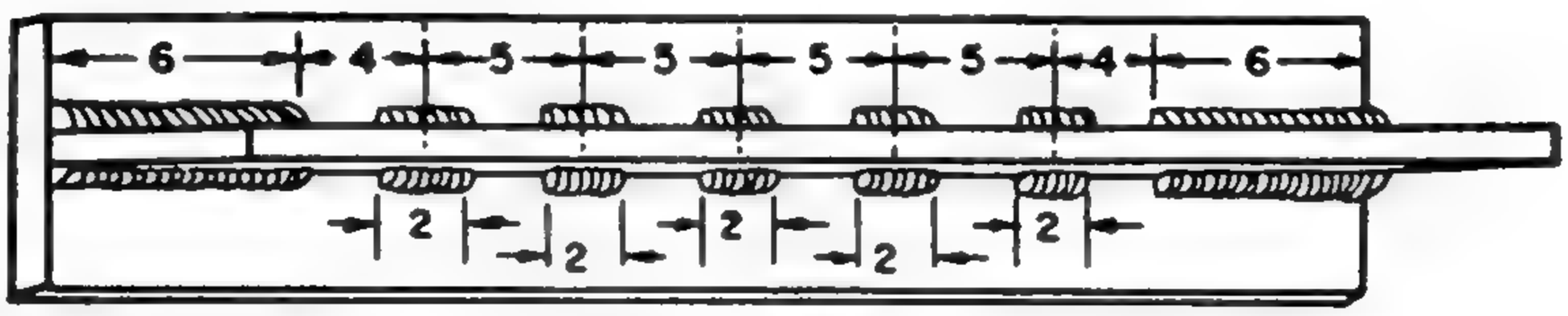
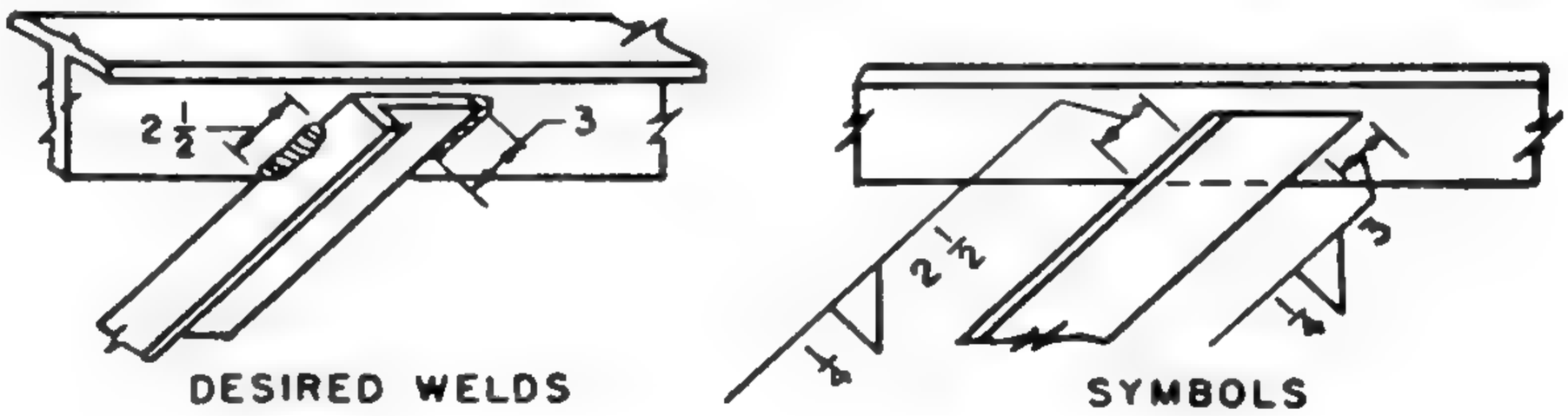


Fig. 22—Application of Dimensions to Intermittent Fillet Welding Symbols

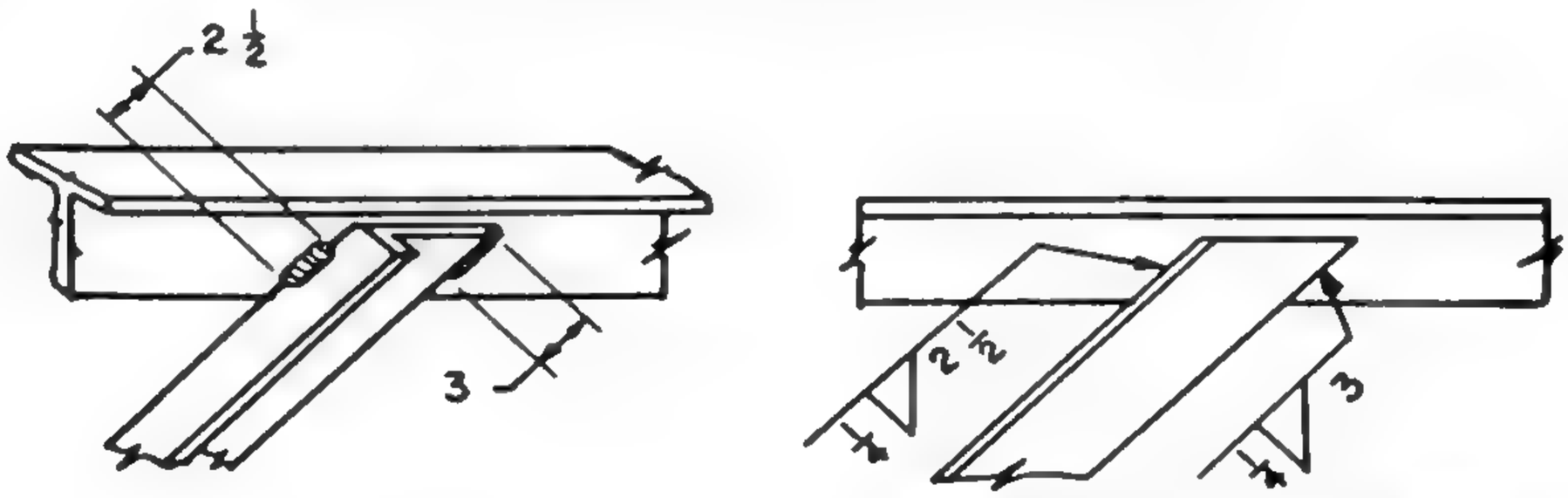


COMBINED INTERMITTENT AND CONTINUOUS WELDING

(A)



(B) WELDS DEFINITELY LOCATED



(C) WELDS APPROXIMATELY LOCATED

Fig. 23—Designation of Location and Extent of Fillet Welds

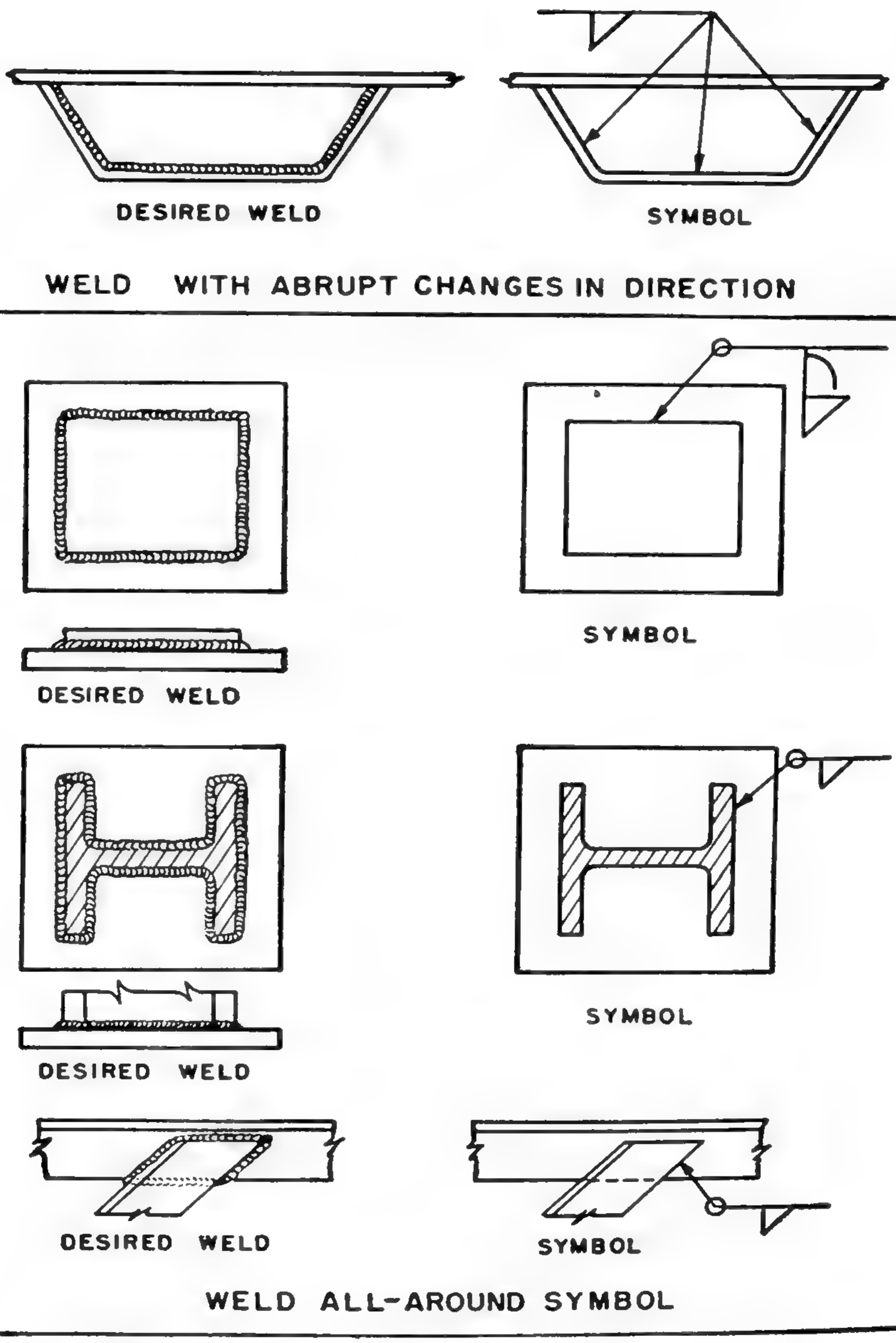


Fig. 24—Designation of Extent of Welding

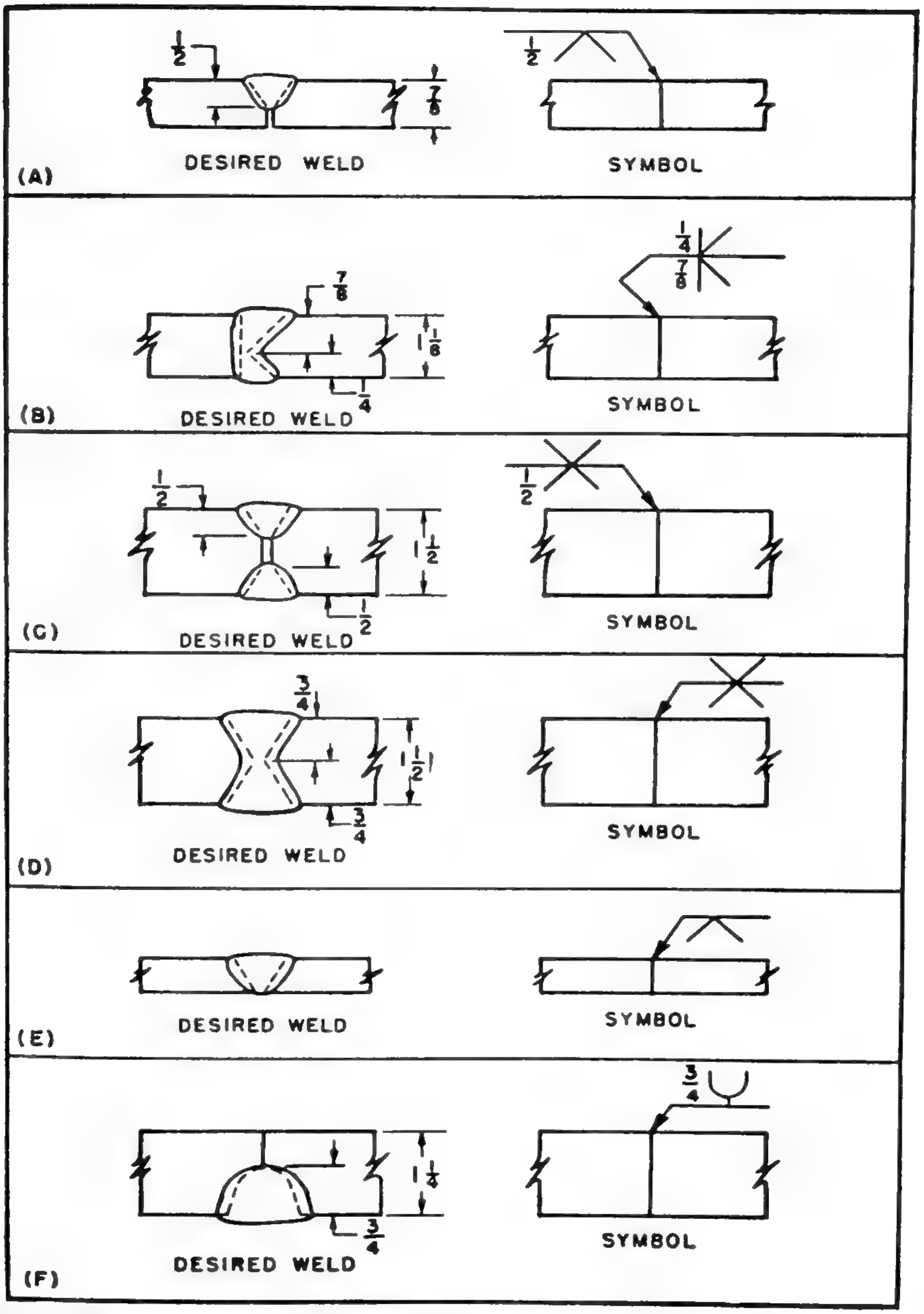


Fig. 25—Designation of Size of Groove Welds with No Specified Root Penetration

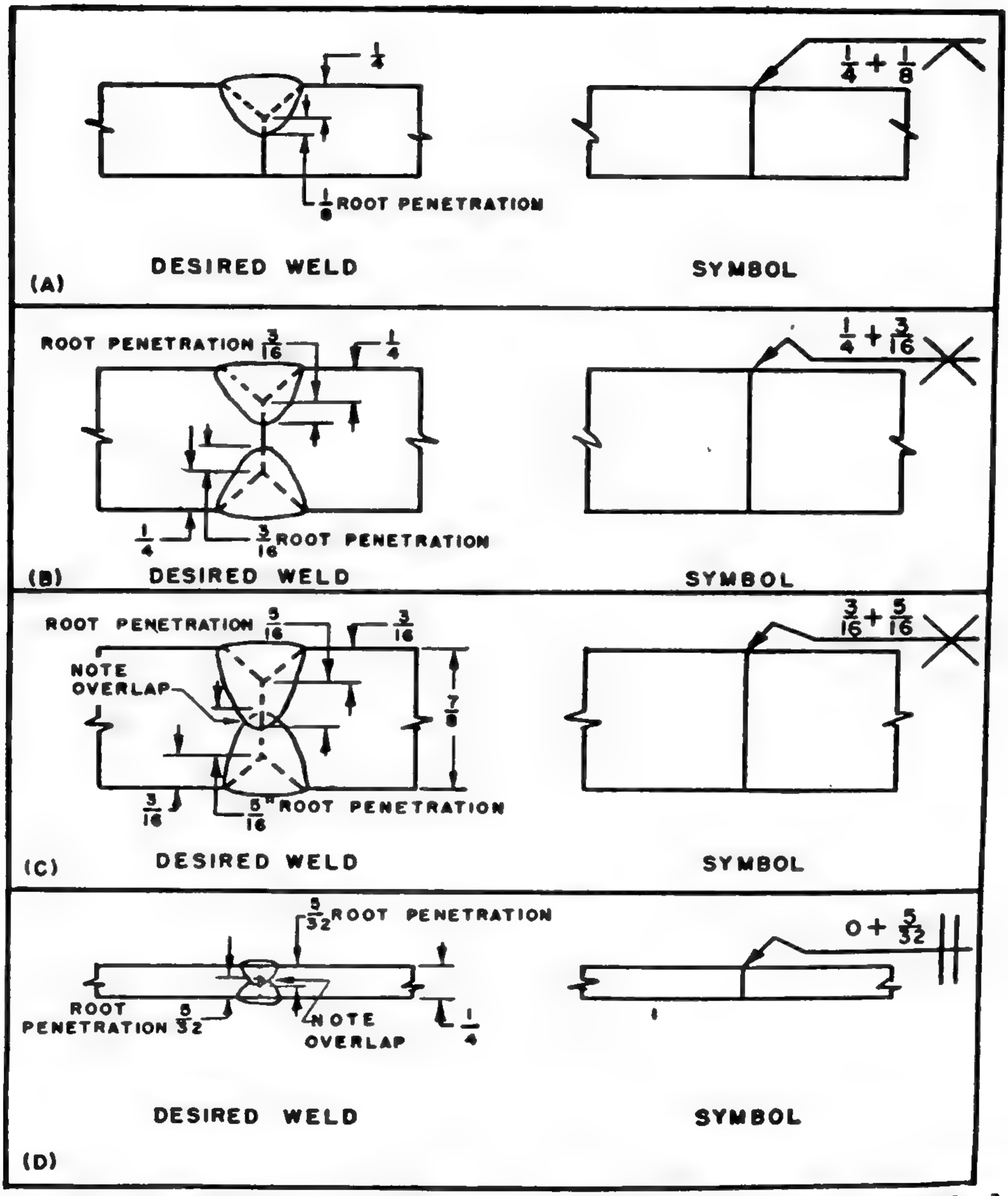


Fig. 26—Designation of Size of Groove Welds with Specified Root Penetration

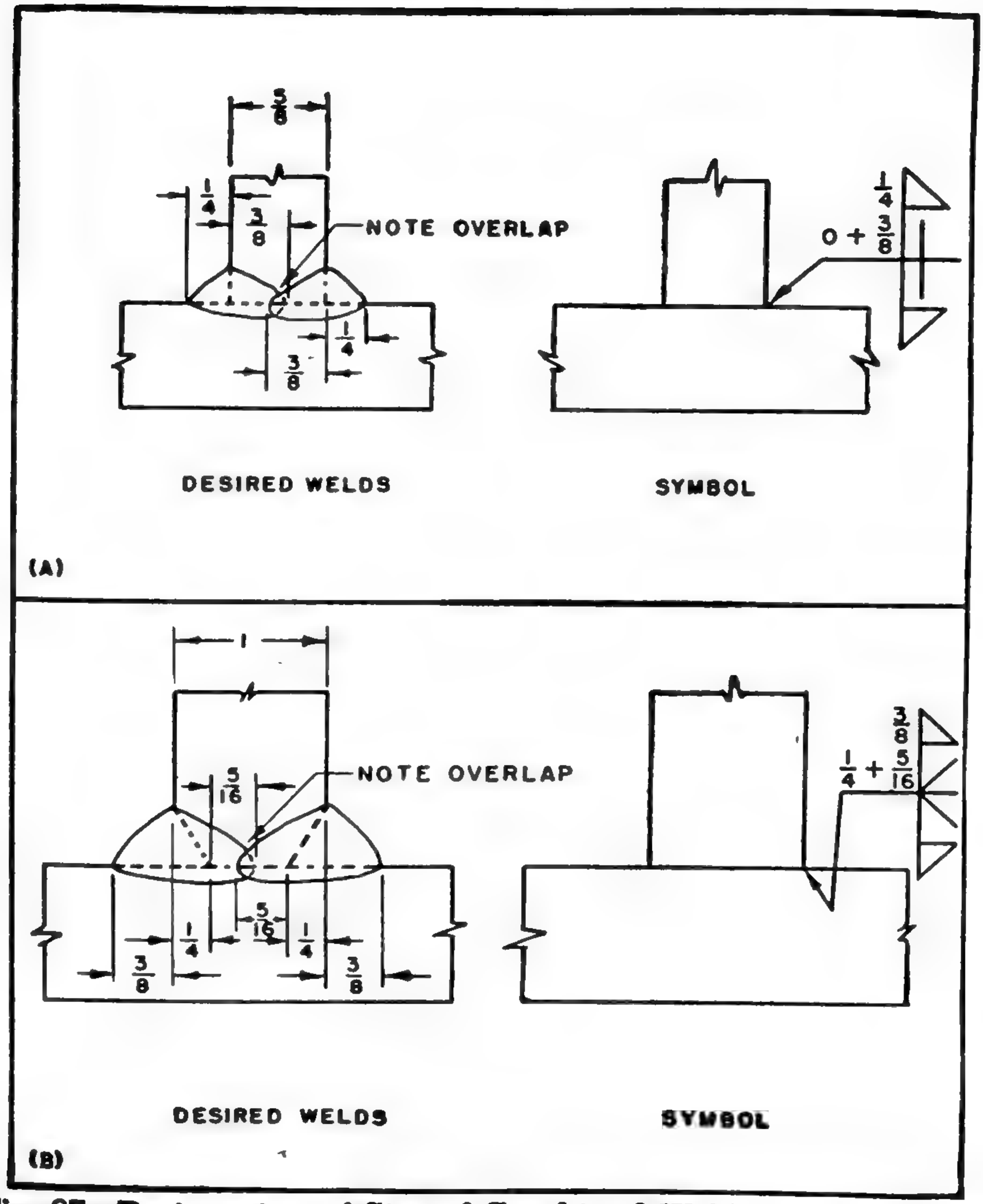


Fig. 27—Designation of Size of Combined Welds with Specified Root Penetration

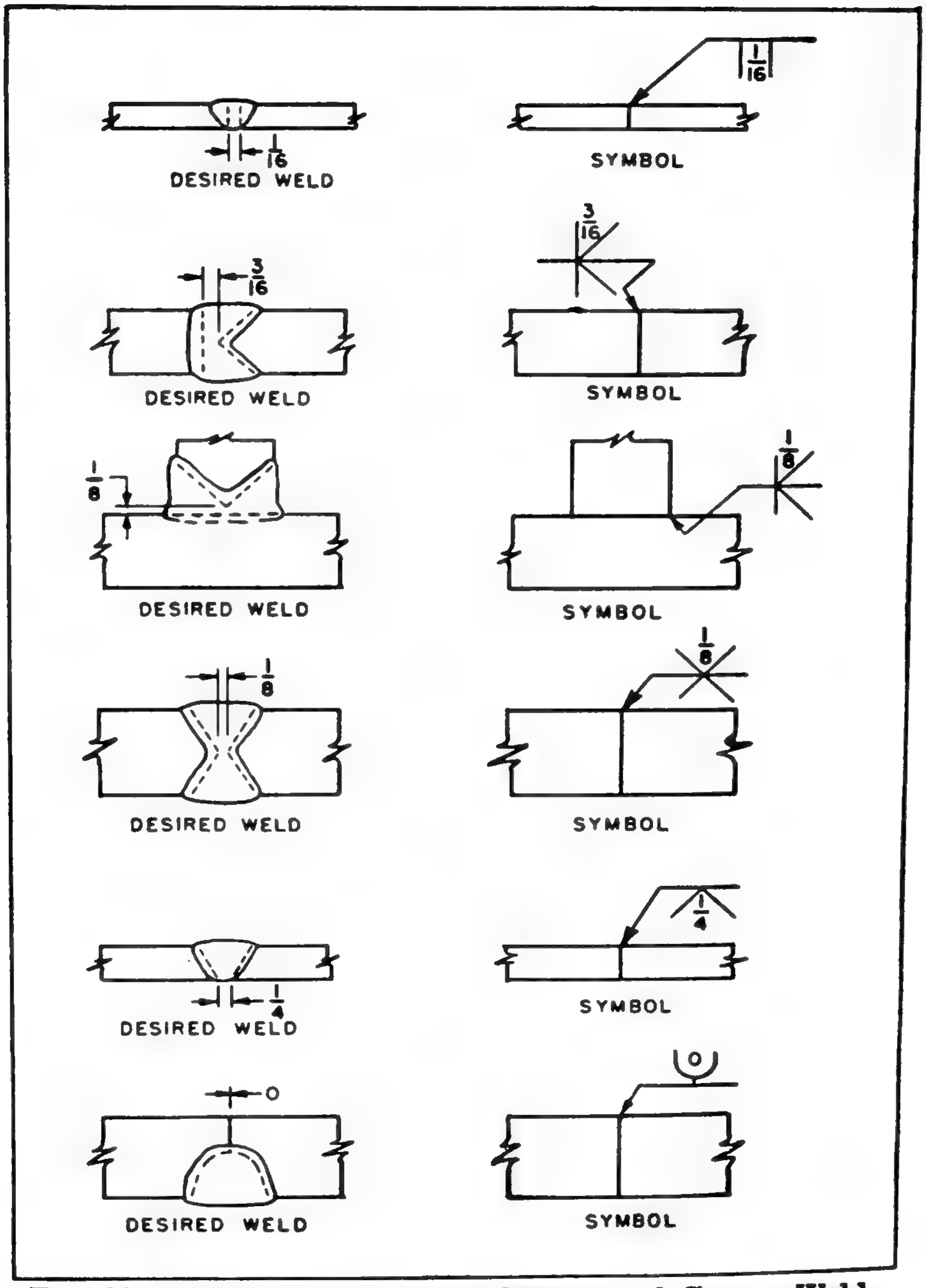


Fig. 28—Designation of Root Opening of Groove Welds

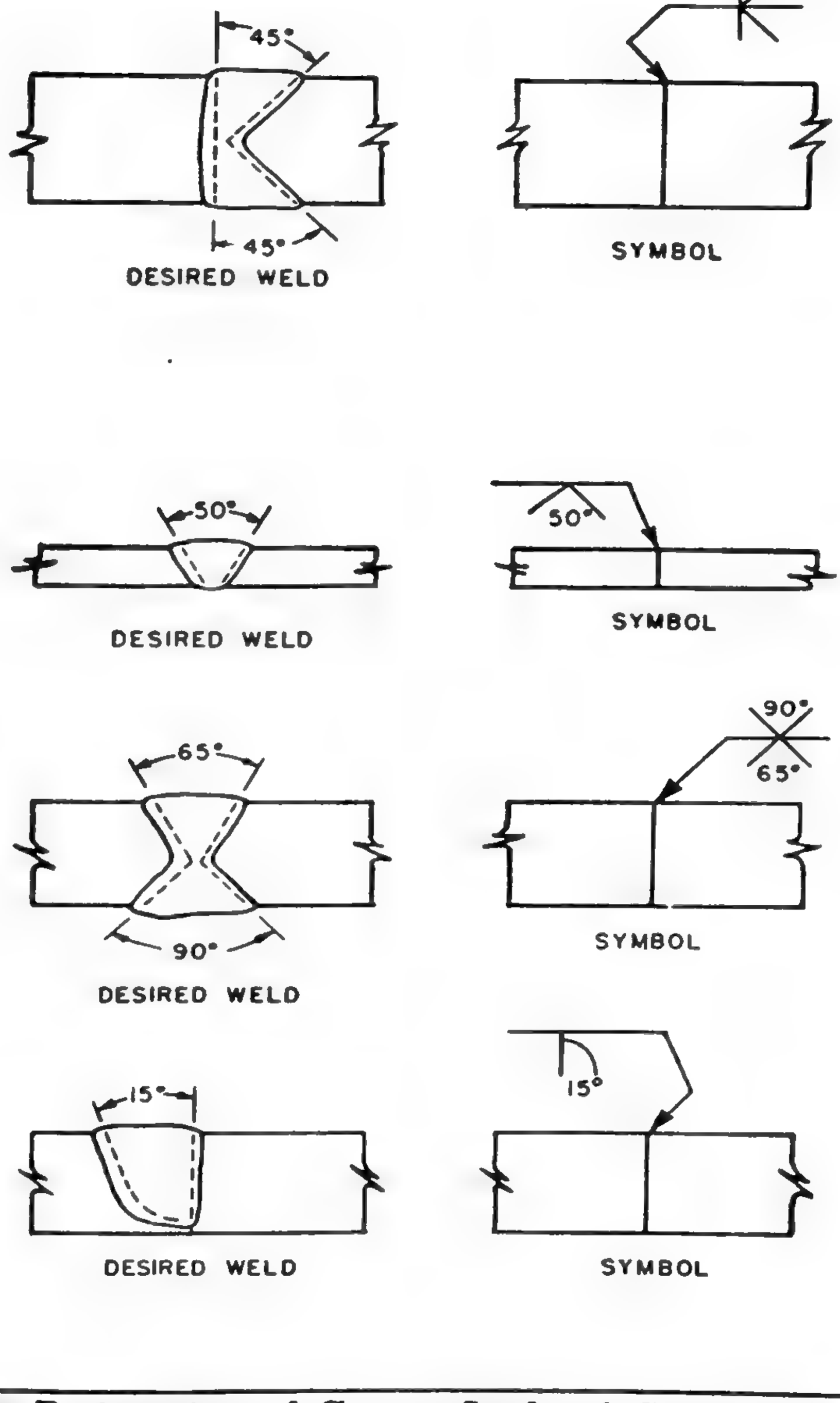


Fig. 29—Designation of Groove Angle of Groove Welds

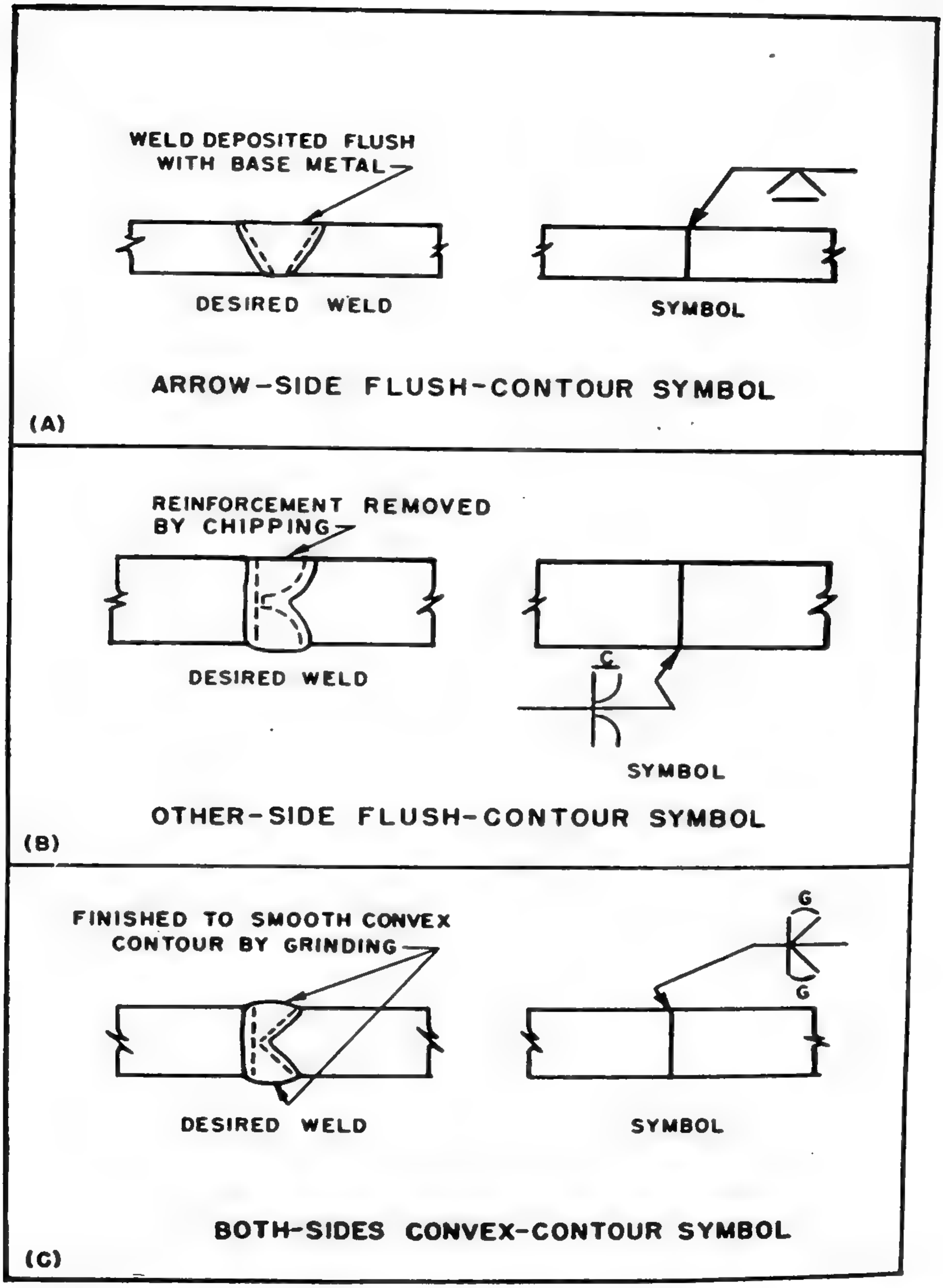
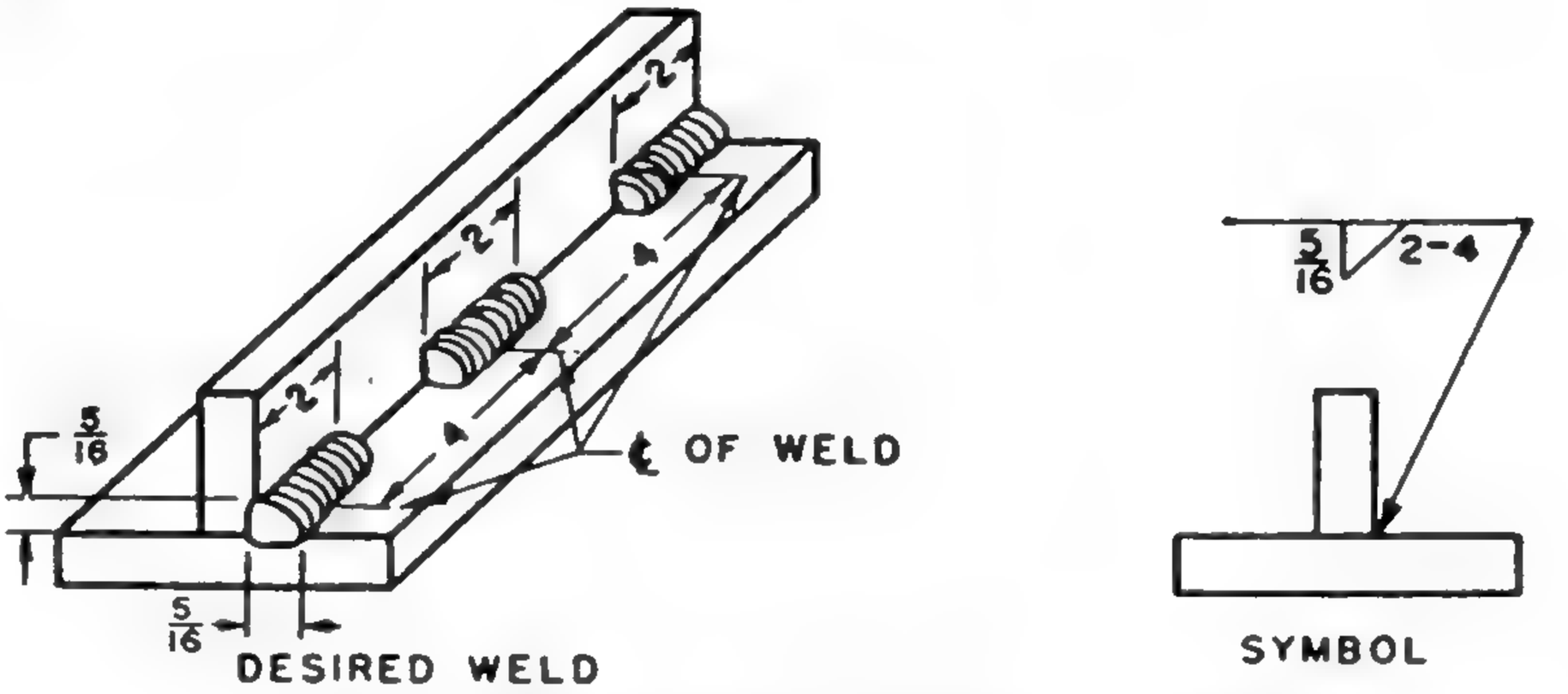
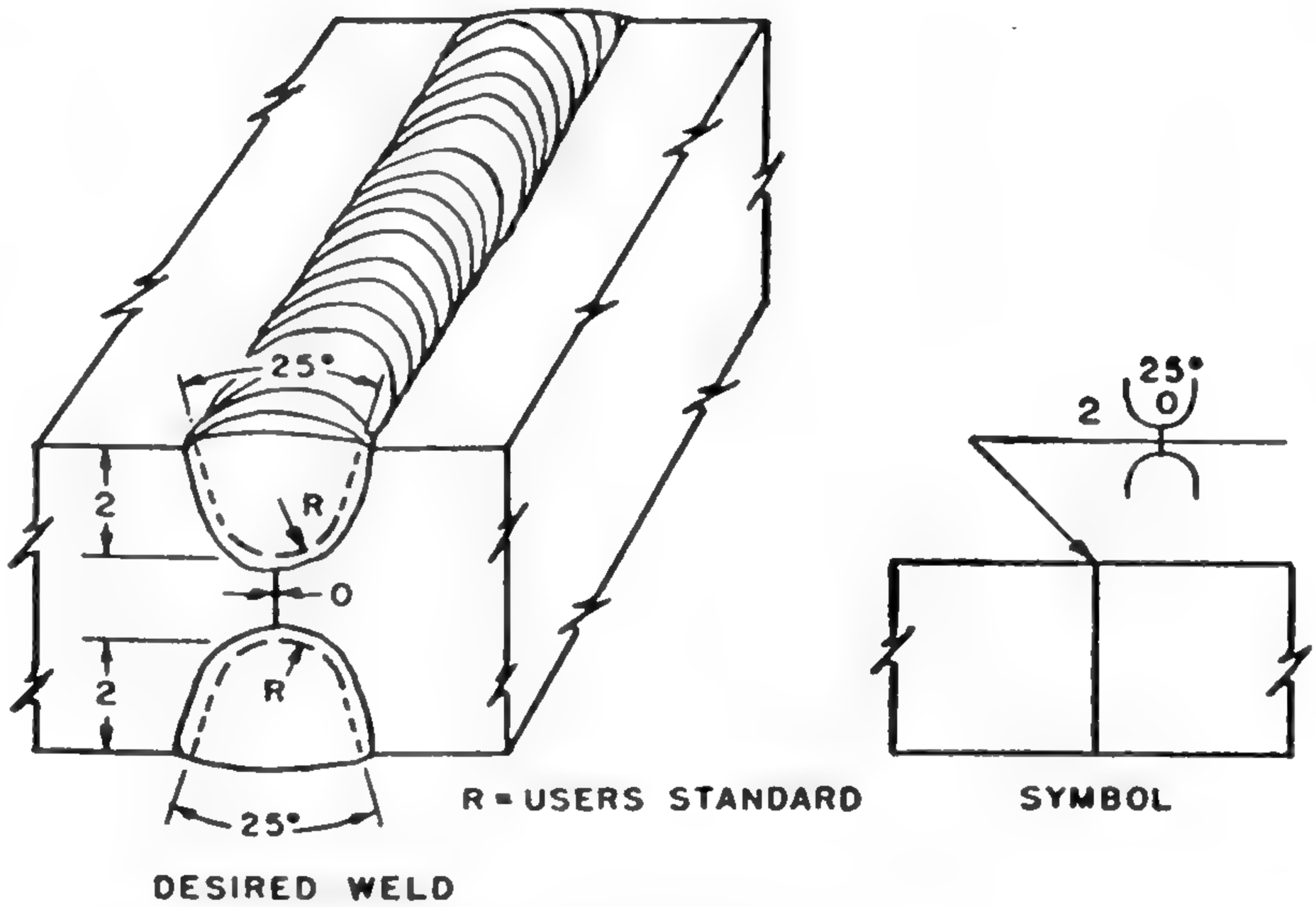


Fig. 30—Application of Flush- and Convex-Contour Symbols to Groove Welding Symbols



FILLET WELDING SYMBOL SHOWING
USE OF COMBINED DIMENSIONS

(A)



GROOVE WELDING SYMBOL SHOWING
USE OF COMBINED DIMENSIONS

(B)

Fig. 31—Application of Dimensions to Fillet and Groove Welding Symbols

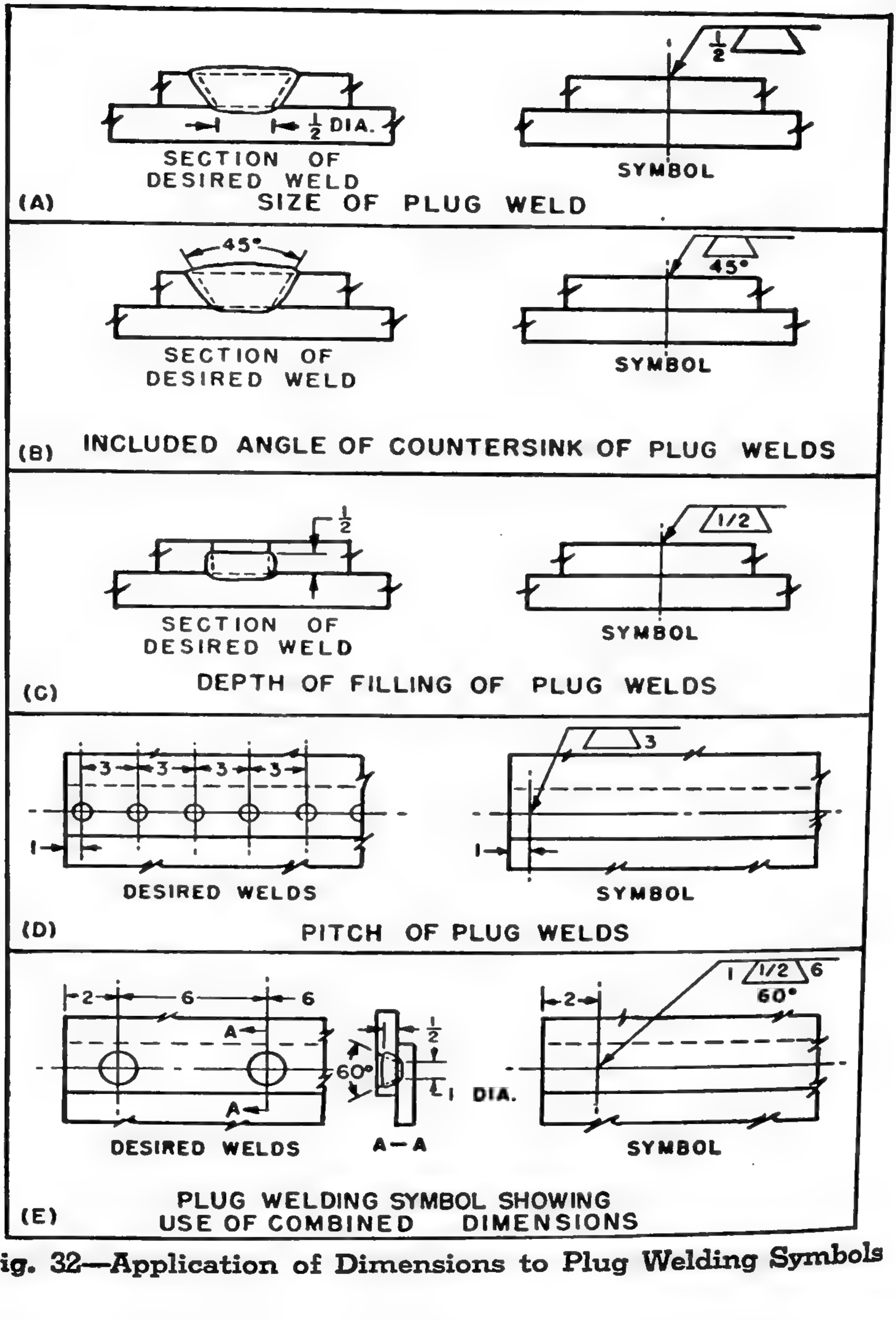
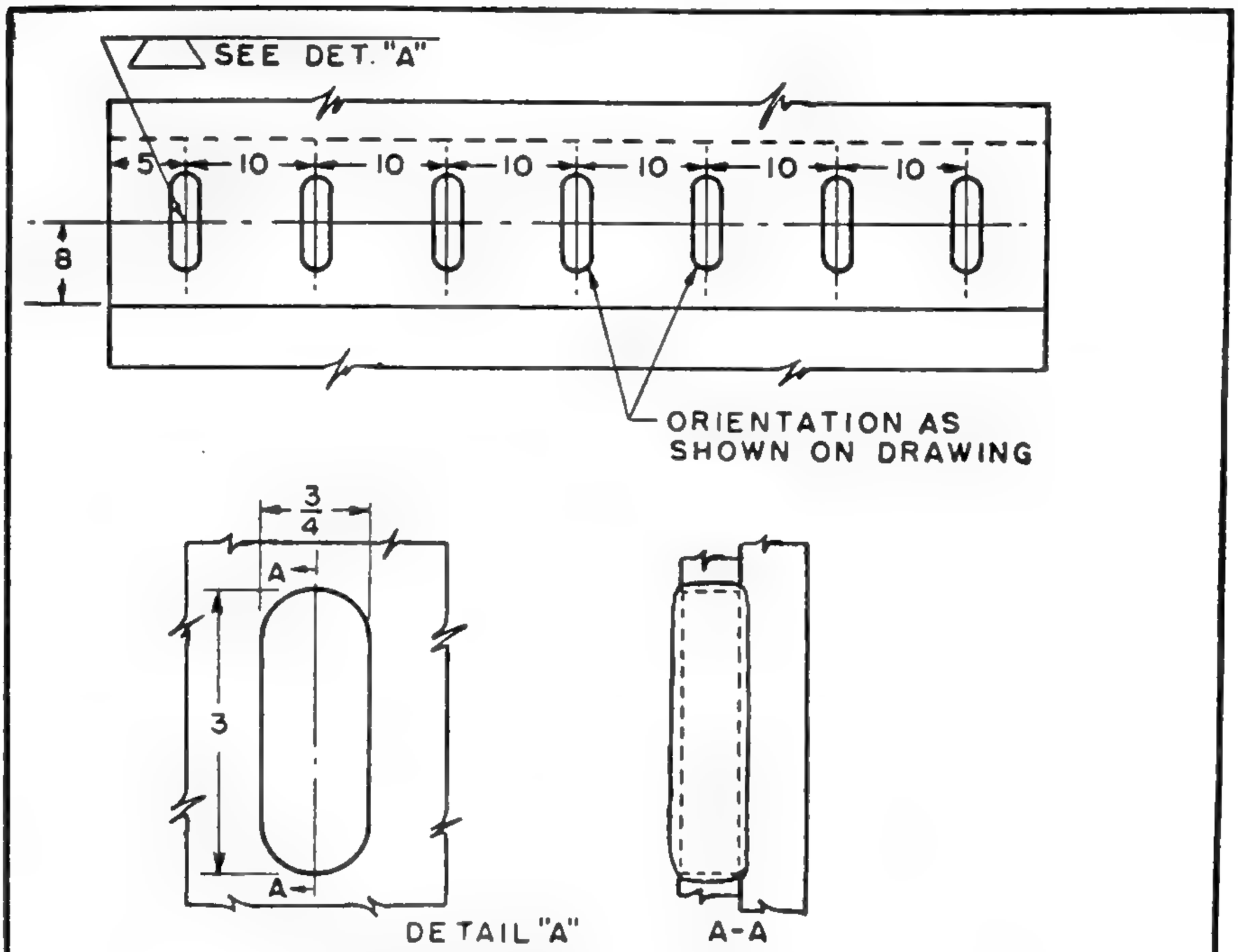
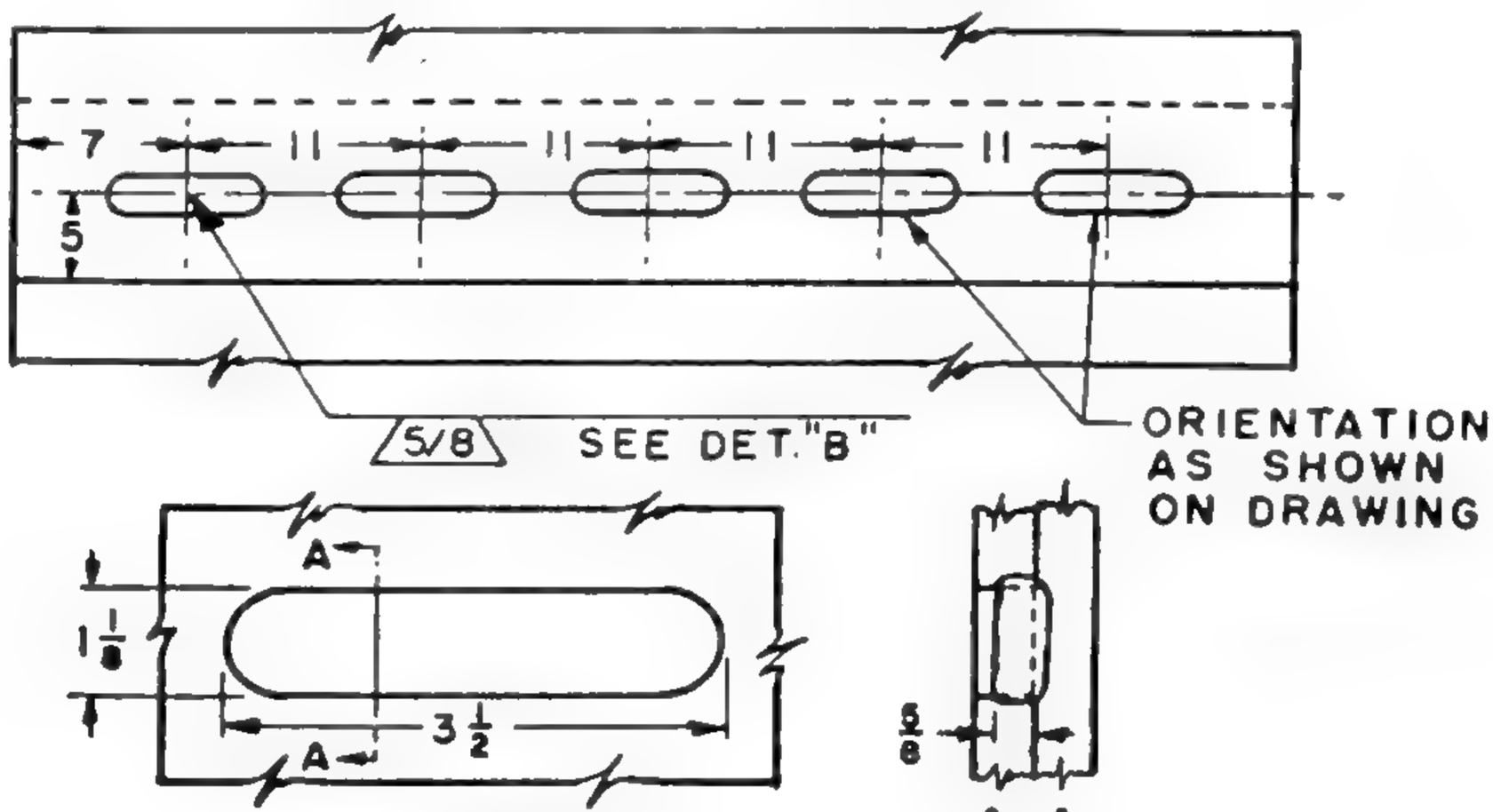


Fig. 32—Application of Dimensions to Plug Welding Symbols



(A) COMPLETELY FILLED SLOT WELDS



(B) PARTIALLY FILLED SLOT WELDS

Fig. 33—Application of Dimensions to Slot Welding Symbols

Fig. 34—Application of Dimensions to Spot Welding Symbols

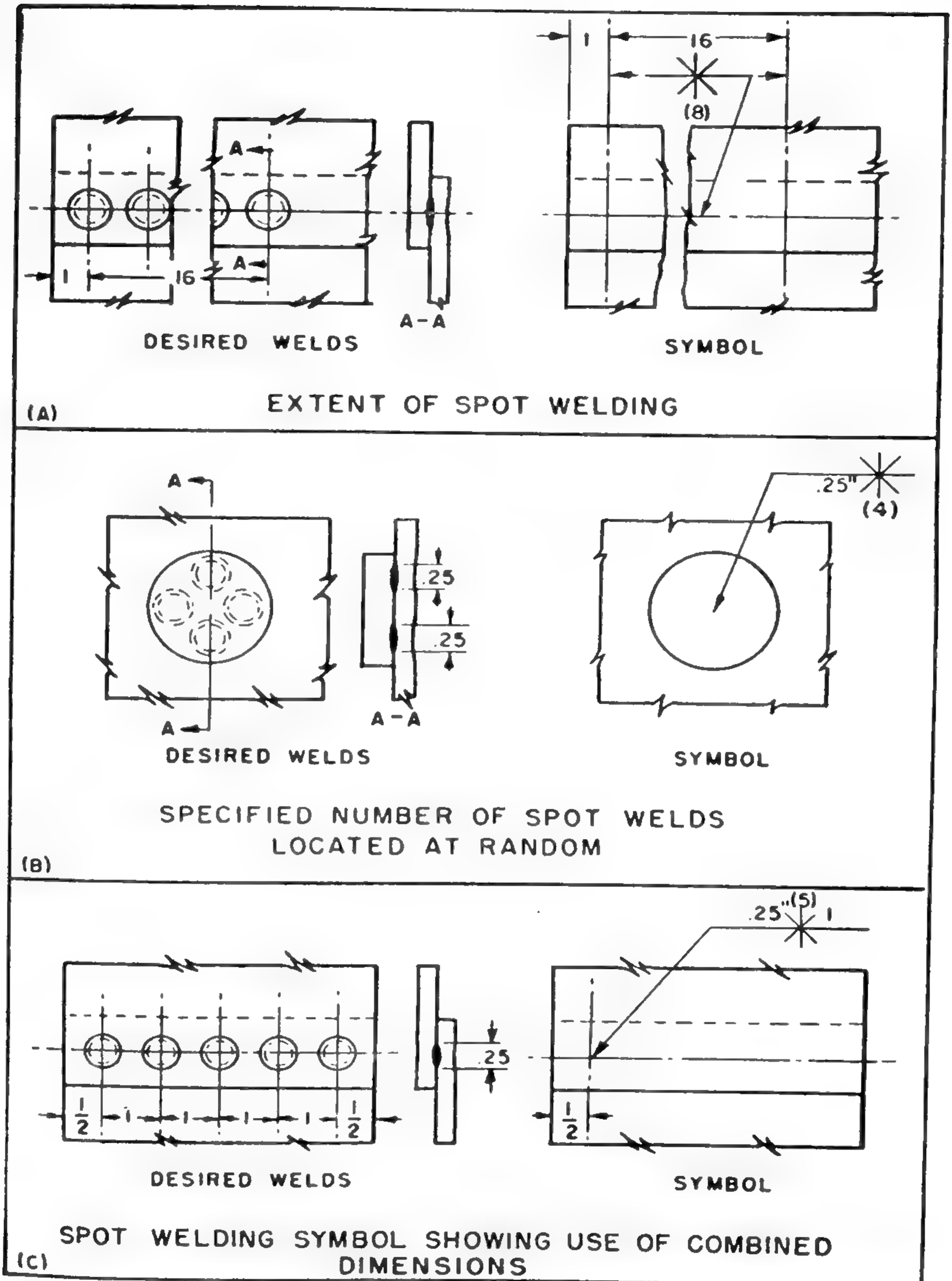


Fig. 35—Application of Dimensions to Spot Welding Symbols

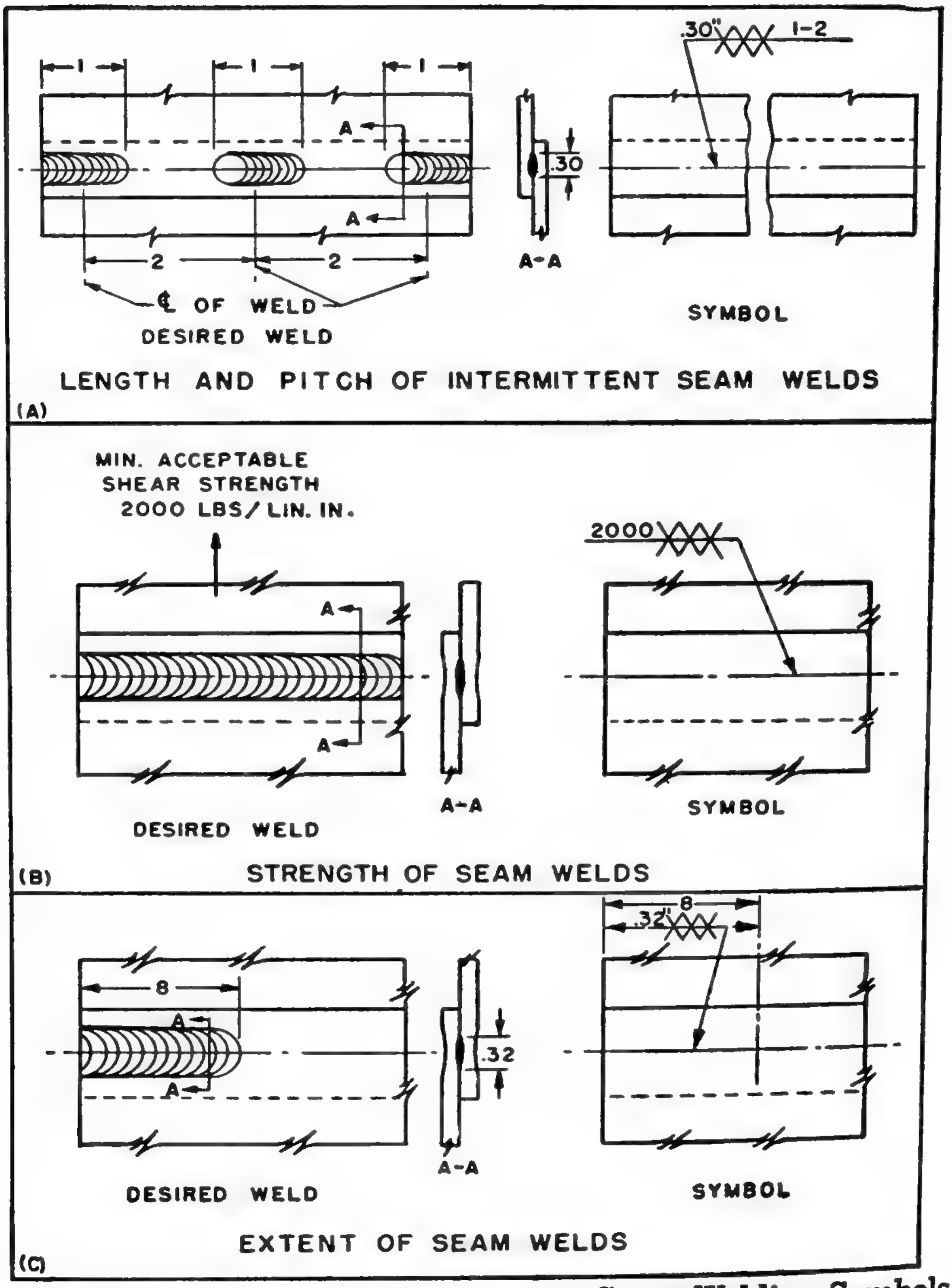


Fig. 36—Application of Dimensions to Seam Welding Symbols

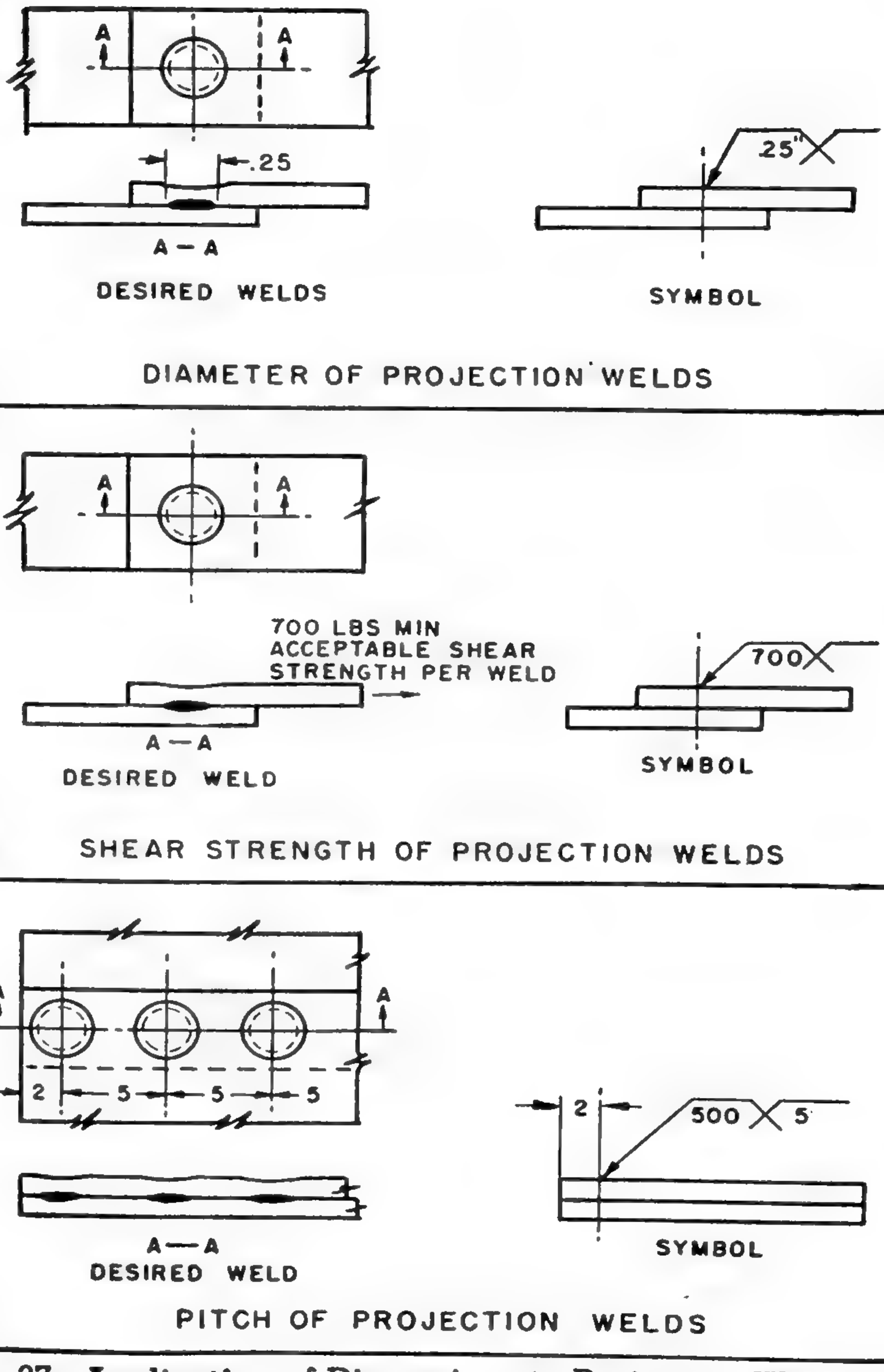
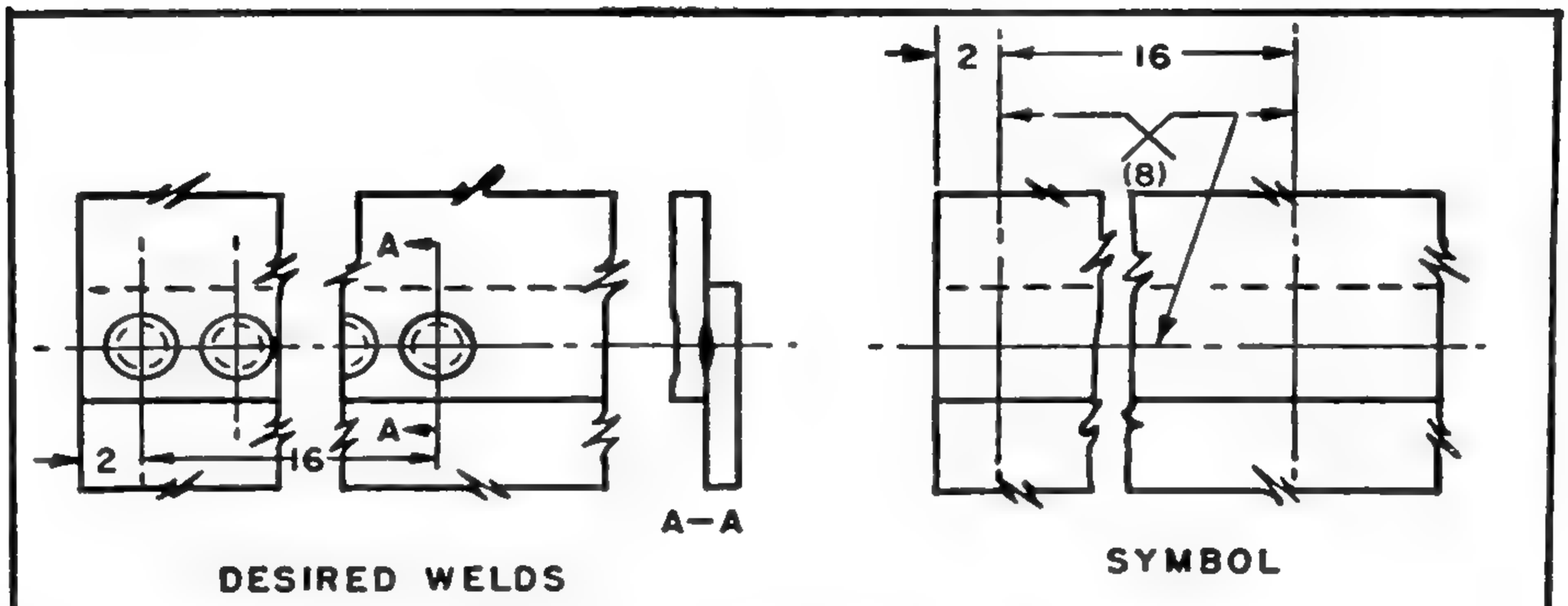
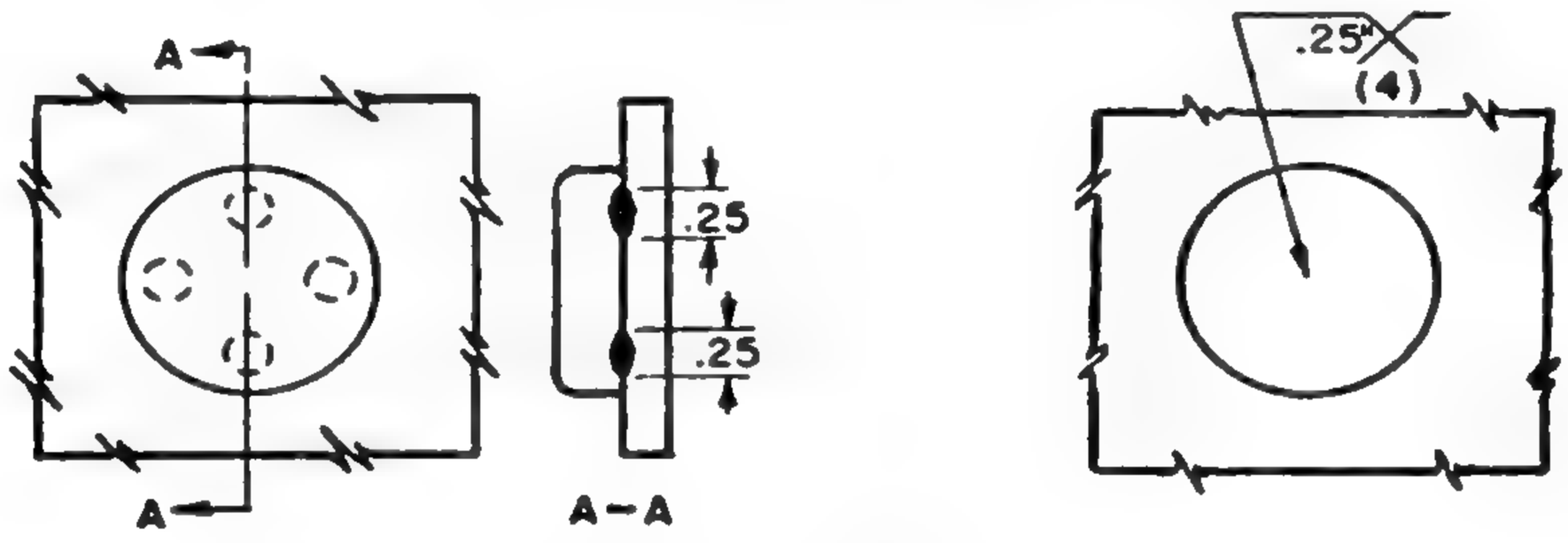


Fig. 37—Application of Dimensions to Projection Welding Symbols

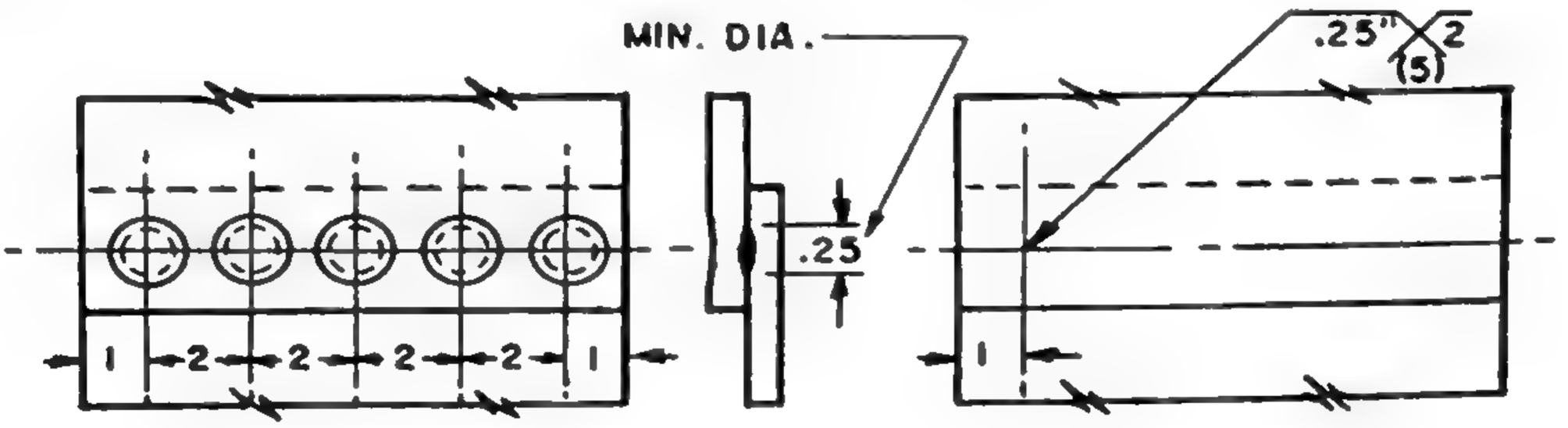


(A) EXTENT OF PROJECTION WELDING



SPECIFIED NUMBER OF PROJECTION WELDS LOCATED AT RANDOM

(B)



PROJECTION WELDING SYMBOL SHOWING USE OF COMBINED DIMENSIONS

(C)

Fig. 38—Application of Dimensions to Projection Welding Symbols

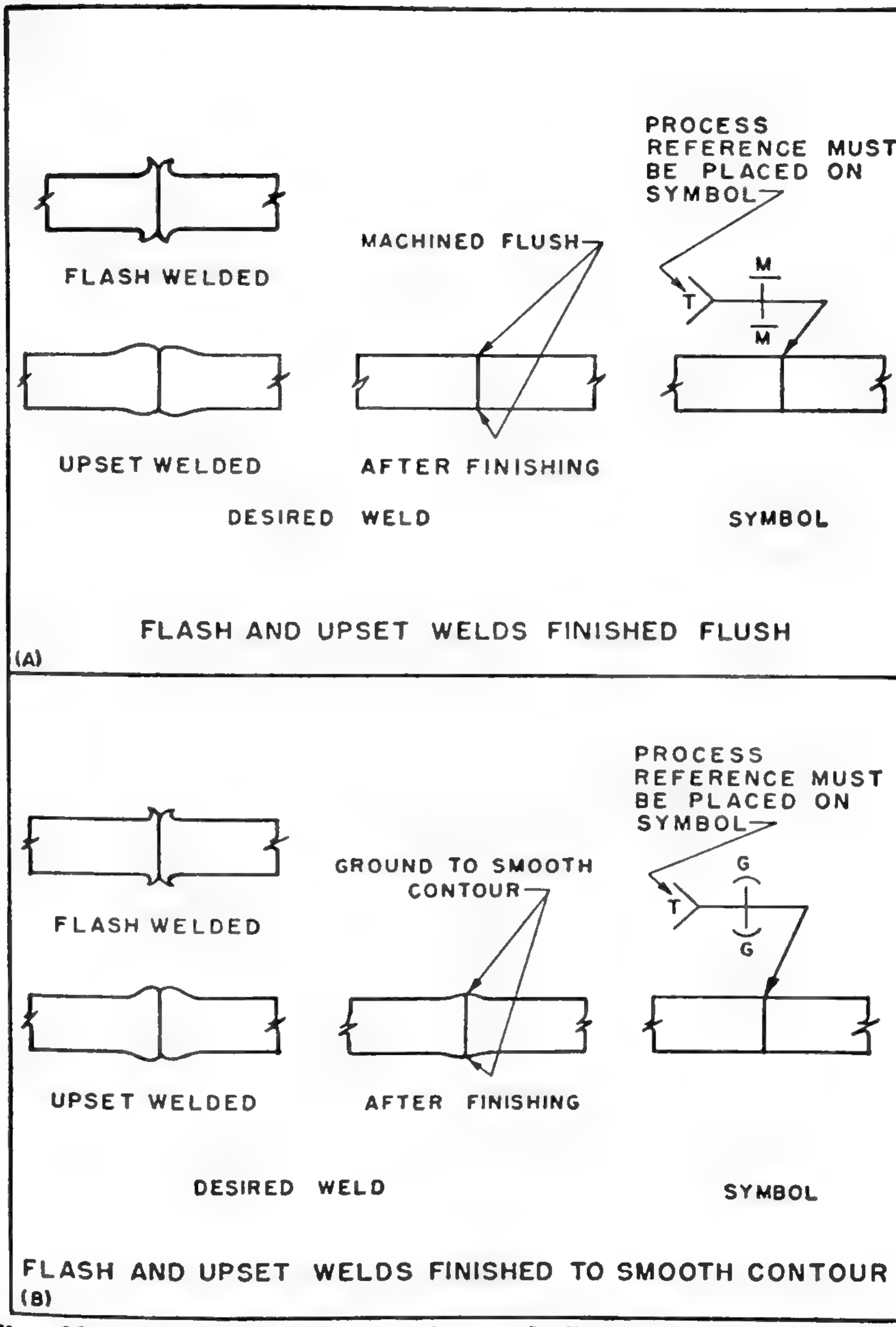


Fig. 39—Application of Flush- and Convex-Contour Symbol to Flash and Upset Welding Symbols

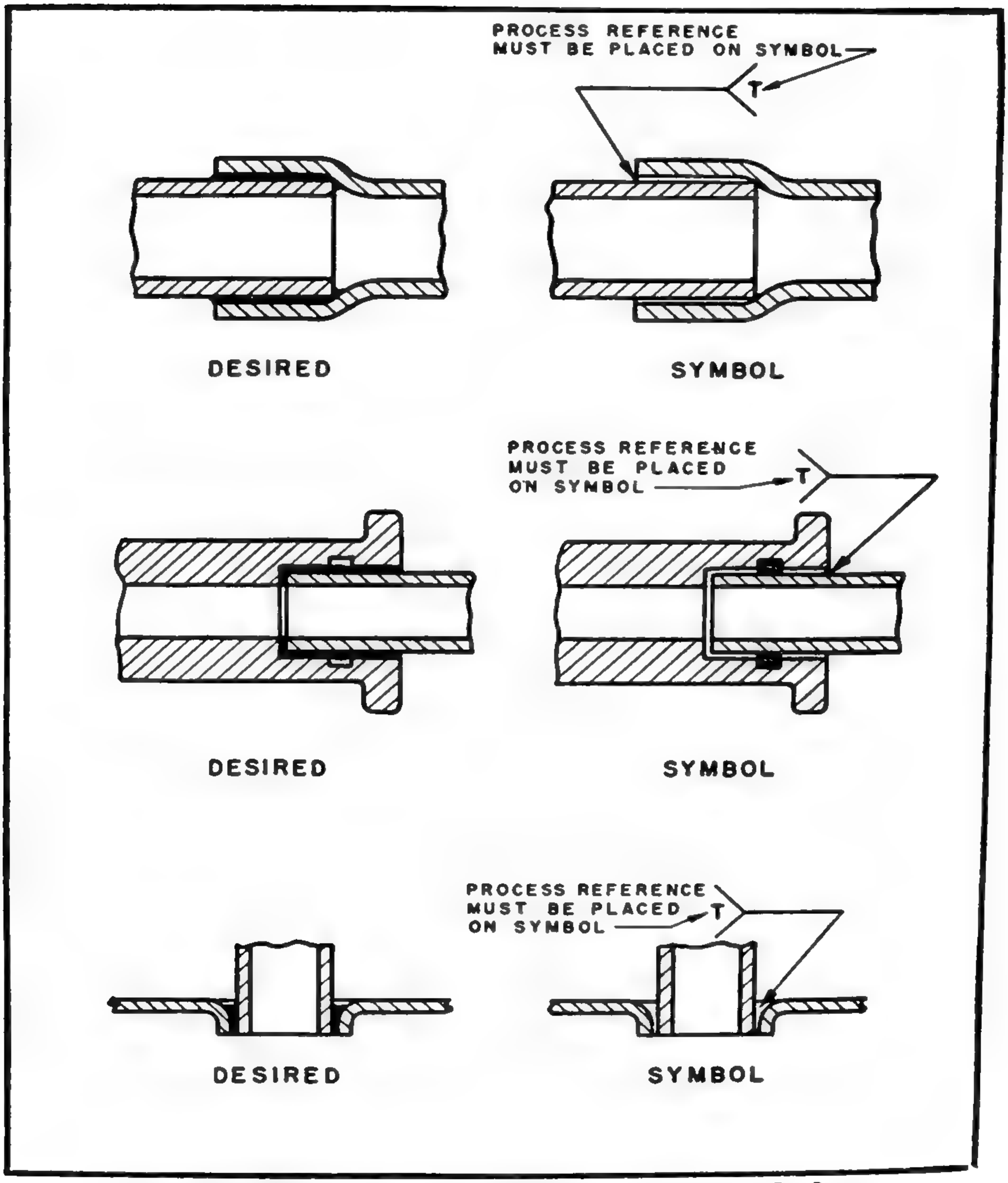


Fig. 40—Application of Brazing Symbols

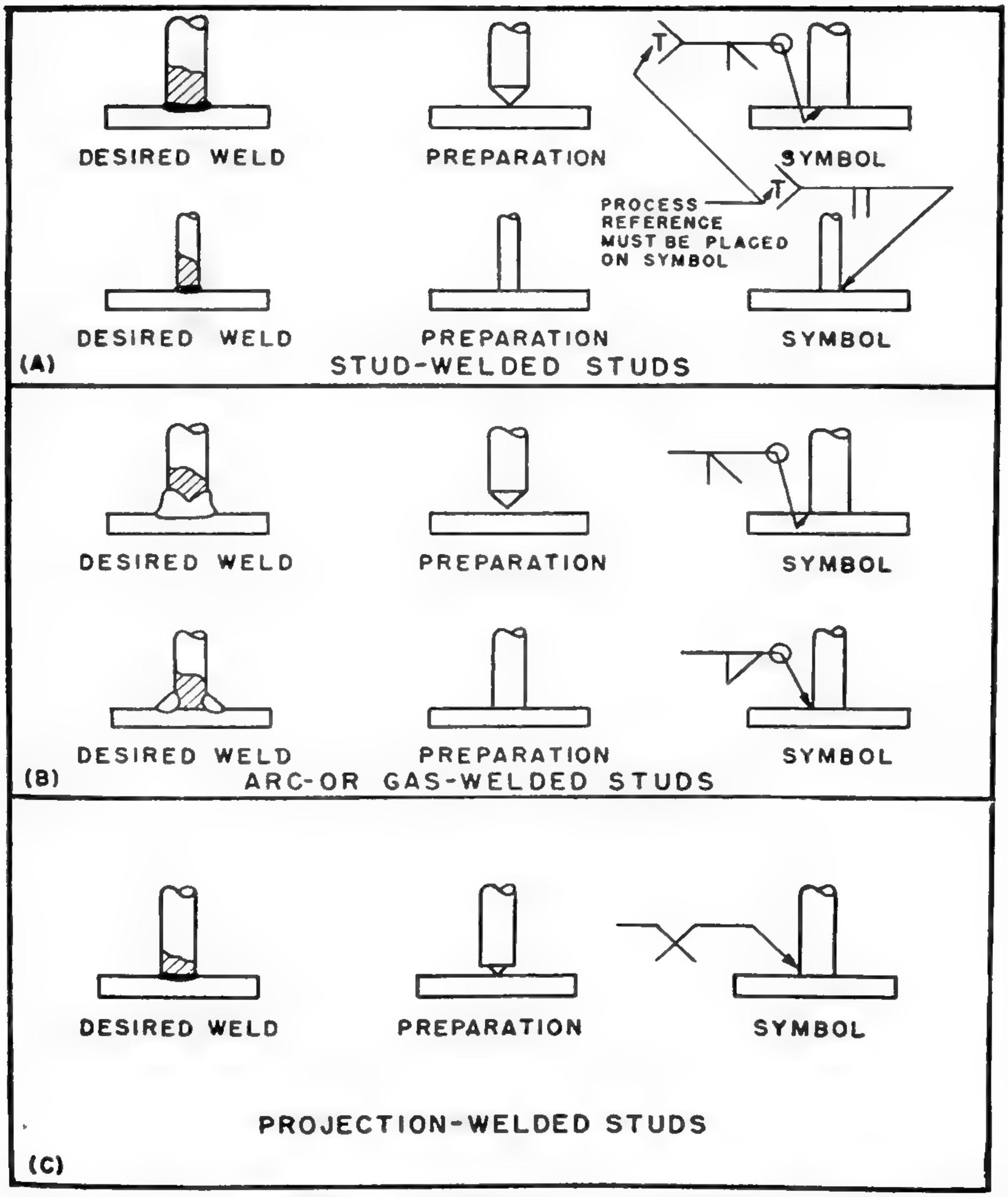


Fig. 41—Use of Welding Symbols to Indicate the Welding of Studs

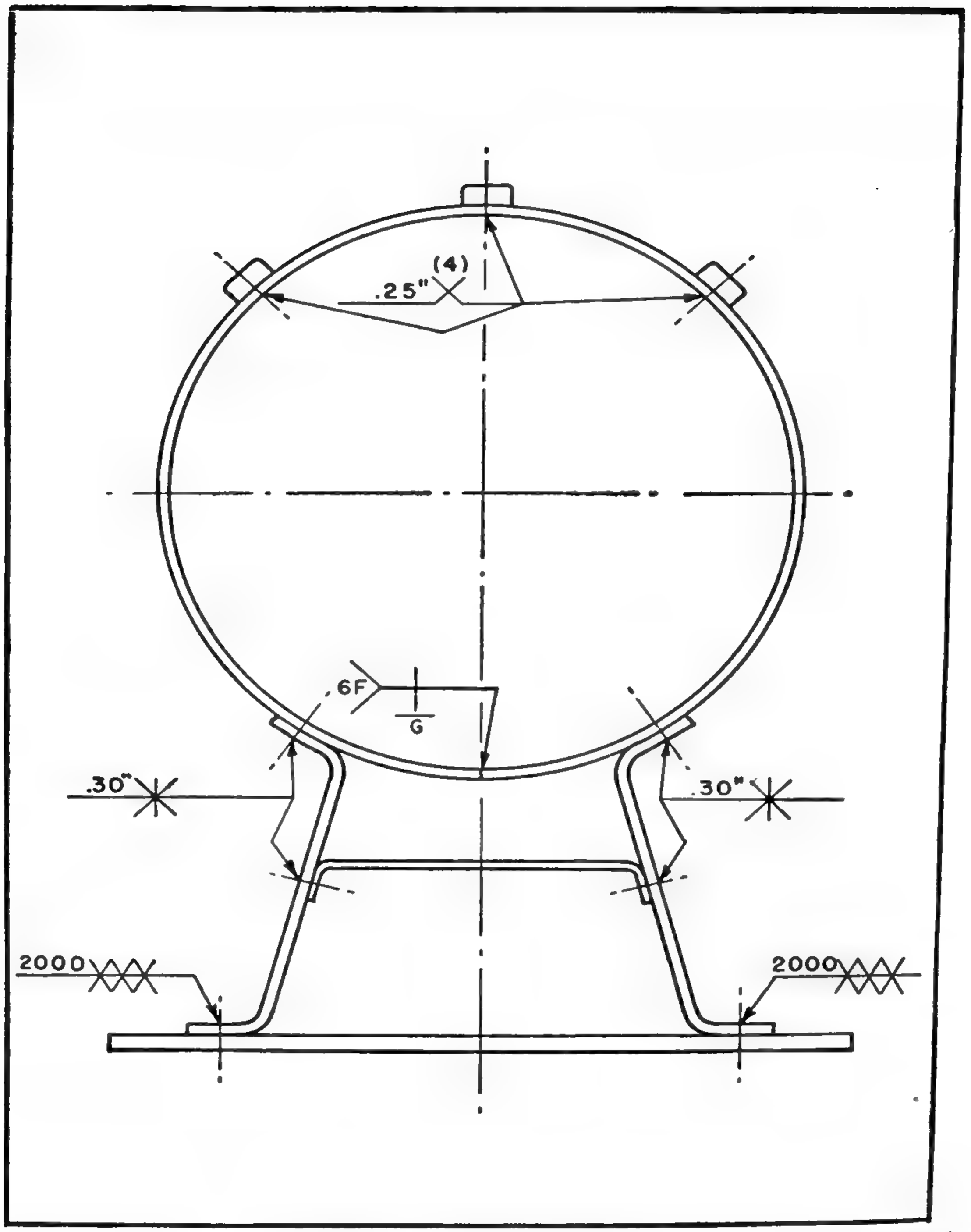


Fig. 42—Use of Resistance Welding Symbols on Sheet-Metal Fabrication Drawing

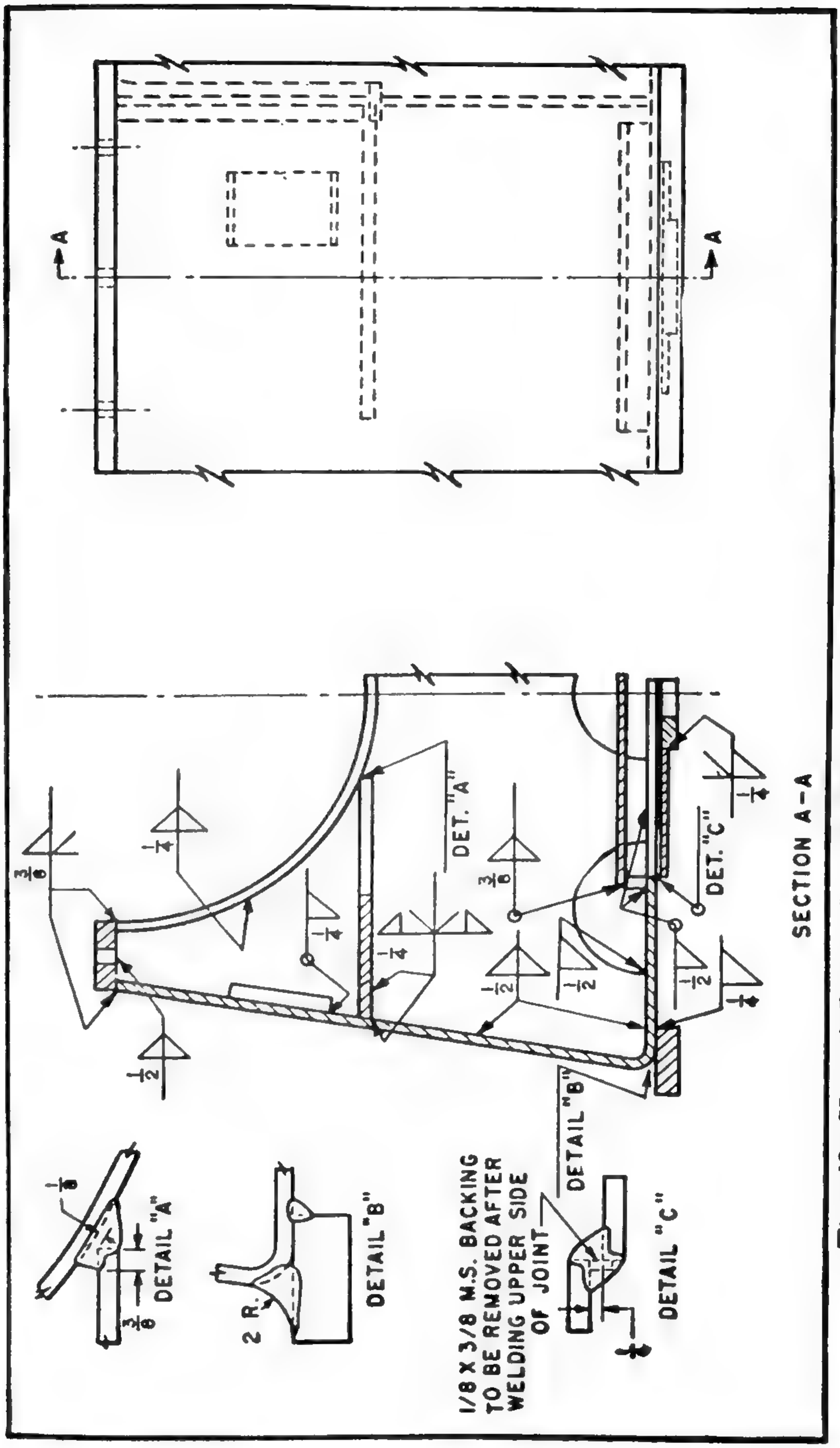


Fig. 43—Use of Arc and Gas Welding Symbols on Machinery Drawing

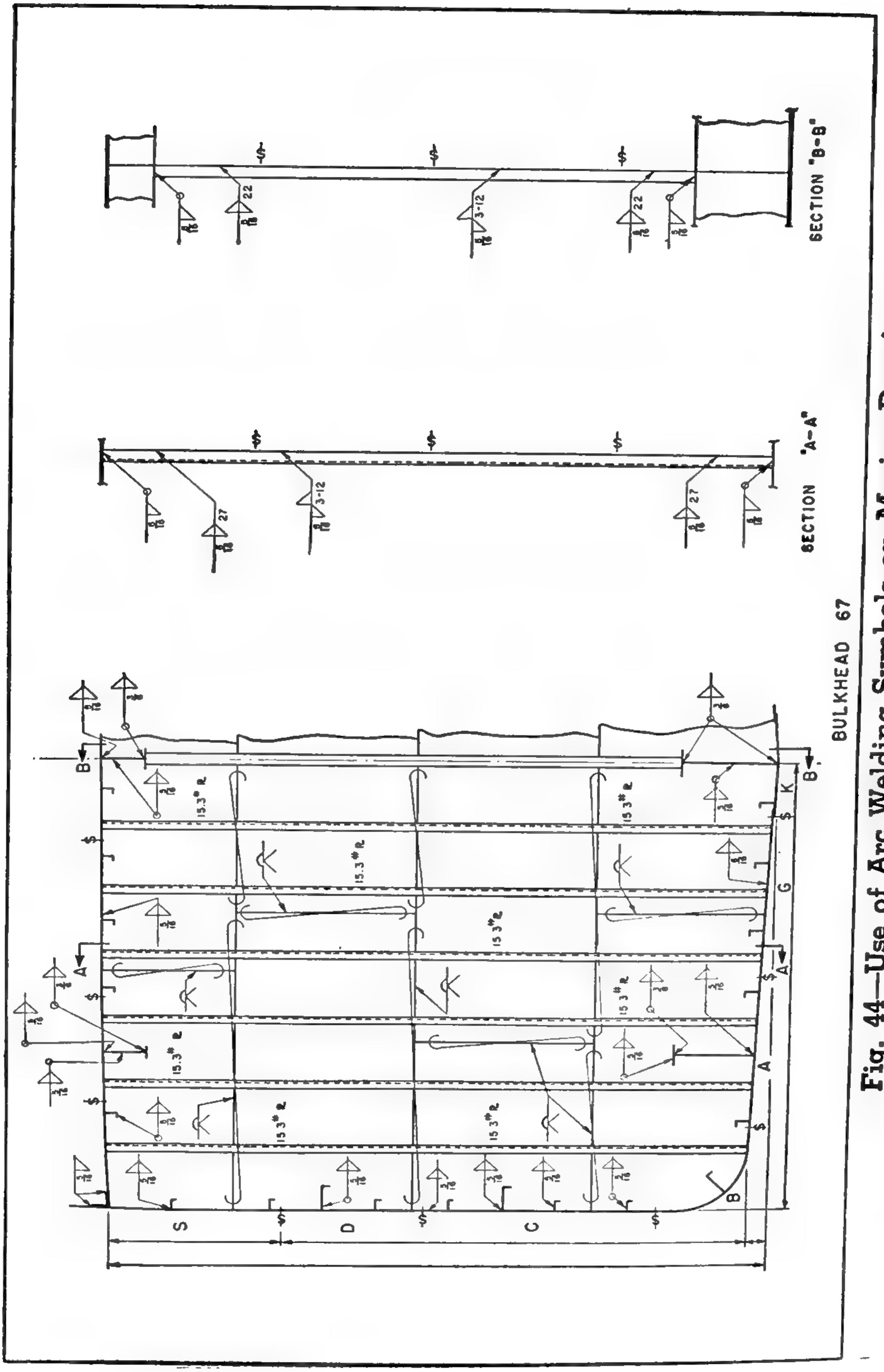


Fig. 44—Use of Arc Welding Symbols on Marine Drawing

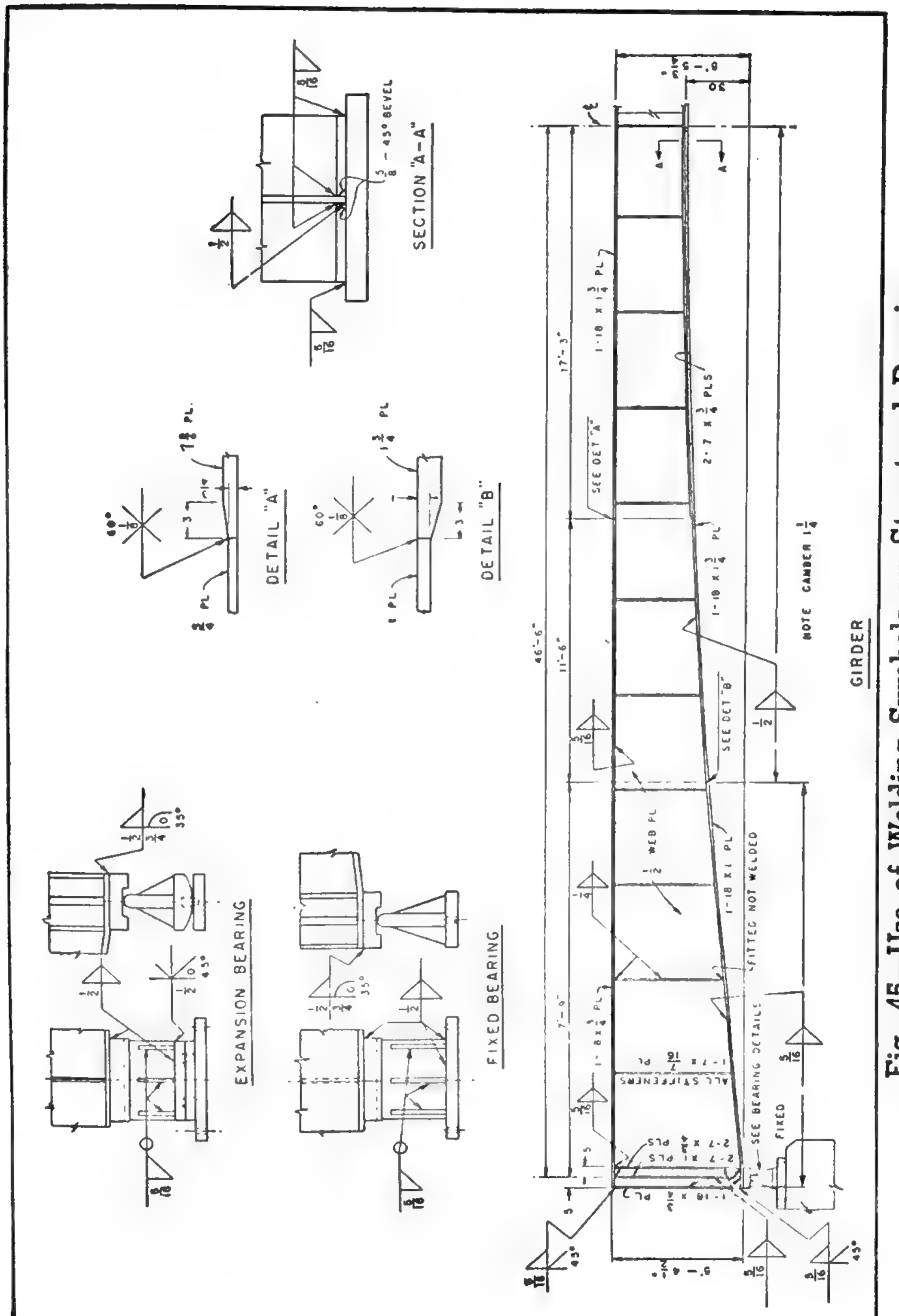
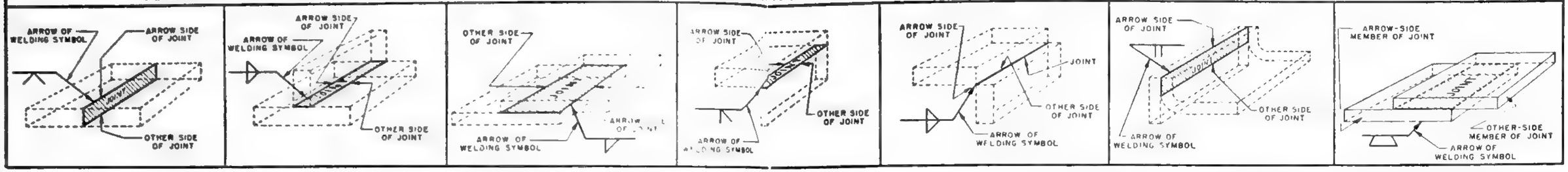


Fig. 45—Use of Welding Symbols on Structural Drawing

AMERICAN WELDING SOCIETY

SUMMARY OF STANDARD WELDING SYMBOLS

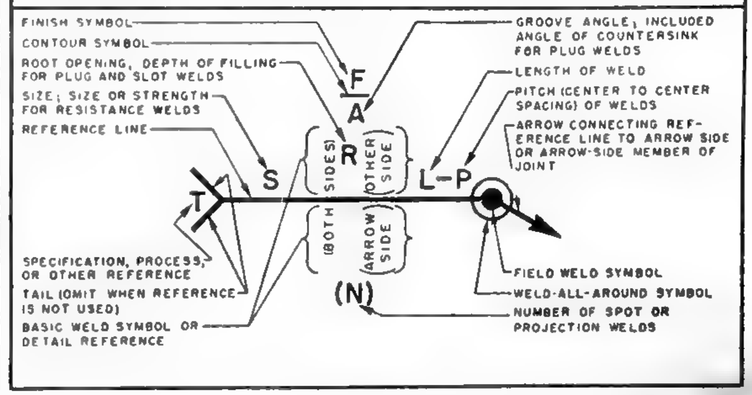
IDENTIFICATION OF *ARROW* SIDE AND *OTHER* SIDE OF JOINT AND *ARROW*-SIDE AND *OTHER*-SIDE *MEMBER* OF JOINT



BASIC WELDING SYMBOLS

LOCATION SIGNIFICANCE	ARC AND GAS WELDING SYMBOLS								RESISTANCE WELDING SYMBOLS			
	BEAD	FILLET	PLUG OR SLOT	GROOVE: SQUARE	GROOVE: V	GROOVE: BEVEL	GROOVE: U	GROOVE: J	PROJECTION	SPOT	SEAM	FLASH OR UPSET
ARROW SIDE	GROOVE WELD SYMBOL									NOT USED	NOT USED	NOT USED
OTHER SIDE	GROOVE WELD SYMBOL									NOT USED	NOT USED	NOT USED
BOTH SIDES	NOT USED		NOT USED						NOT USED	NOT USED	NOT USED	NOT USED
NO ARROW-SIDE OR OTHER SIDE SIGNIFICANCE		NOT USED	NOT USED	NOT USED	NOT USED	NOT USED	NOT USED	NOT USED	NOT USED			

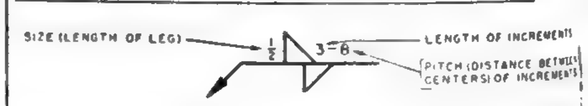
LOCATION OF ELEMENTS OF A WELDING SYMBOL



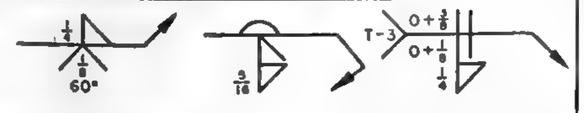
TYPICAL WELDING SYMBOLS

BEAD WELD SYMBOL INDICATING BEAD TYPE BACK WELD

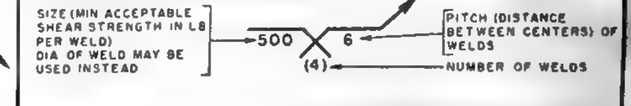
STAGGERED INTERMITTENT-FILLET WELDING SYMBOL



WELDING SYMBOLS FOR COMBINED WELDS

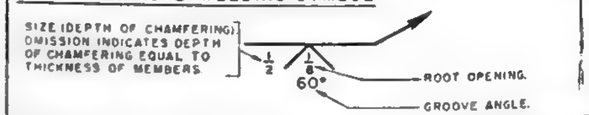


PROJECTION WELDING SYMBOL

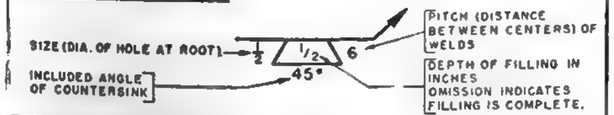


DUAL BEAD WELD SYMBOL INDICATING BUILT-UP SURFACE

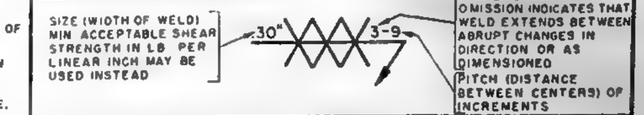
SINGLE-V GROOVE WELDING SYMBOL



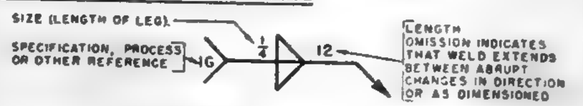
PLUG WELDING SYMBOL



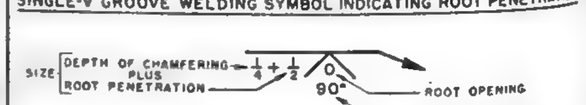
SEAM WELDING SYMBOL



DOUBLE-FILLET WELDING SYMBOL



SINGLE-V GROOVE WELDING SYMBOL INDICATING ROOT PENETRATION



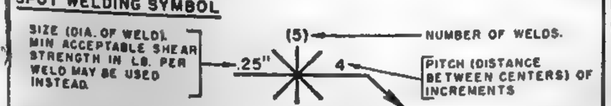
SLOT WELDING SYMBOL

FLASH OR UPSET WELDING SYMBOL

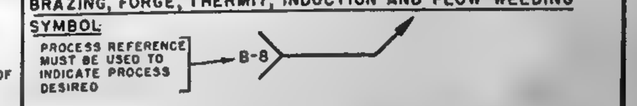
CHAIN-INTERMITTENT-FILLET WELDING SYMBOL

DOUBLE-BEVEL GROOVE WELDING SYMBOL

SPOT WELDING SYMBOL



BRAZING, FORGE, THERMIT, INDUCTION AND FLOW WELDING SYMBOL

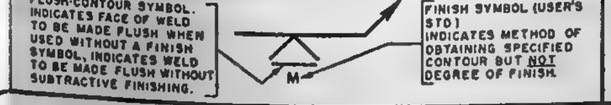


SUPPLEMENTARY SYMBOLS USED WITH WELDING SYMBOLS

WELD-ALL-AROUND SYMBOL

FIELD WELD SYMBOL

FLUSH-CONTOUR SYMBOL



CONVEX-CONTOUR SYMBOL

CHAPTER 59

STANDARD METHODS FOR MECHANICAL TESTING OF WELDS*

FOREWORD

AS FOR any engineering product, the quality of welds depends upon competent inspection and adequate tests. Experience has shown that, in general, mechanical tests to determine their strength and other properties are the least expensive and most reliable tests for the quality of welds. Therefore, they are the tests most widely used. In addition, other tests are used in some cases. No other tests appear likely to replace mechanical tests entirely.

Mechanical tests for welds are similar to the usual mechanical tests for the base metal—plate, tubes, etc., with the changes which have been found necessary to determine the properties of welds. These tests for welds have now been used for a sufficient length of time to indicate quite definitely the properties to be determined and the test procedures which not only give adequate information as to the quality of the weld but are the most practicable for welded fabrications.

Although there is a surprising agreement among welding engineers on the properties to be determined and, in general, the test procedure, there is a wide divergence in the shape and size of the specimens and the details of the test procedure. This considerably increases the cost of making the tests, and decreases the usefulness of the results obtained under different codes and specifications, because they cannot be compared directly. There is no logical reason why for a particular welded fabrication the same size and shape of specimen and the same test procedure should not be used by every one. Standardization in this field has all the advantages to every one concerned that are so generally recognized in other fields and need not be discussed here.

Standardization of the mechanical tests for welds does not necessarily apply to research. It does apply to all tests during commercial production, i.e., what are often called "routine tests."

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* Prepared by the AWS Committee on Standard Tests for Welds.

GENERAL REQUIREMENTS

I. Scope

This standard gives the requirements for the specimens, the testing procedure and the method of obtaining the properties. It is not a specification promulgating required values of the properties. The persons including this standard as a portion of a code or specification for a welded product should state definitely:

1. The one or more tests which are required.
2. The limiting numerical values of the properties and whether they are minimum or maximum.
3. The interpretation, if any, of the properties.

II. Testing Procedure

All tests involving the application of a tensile load to a specimen shall be carried out in accordance with the applicable portions of "Standard Methods of Tension Testing of Metallic Materials," A. S. T. M. Designation E-8.

III. Nomenclature

The terminology used in this standard conforms to the "Standard Definitions of Terms Relating to Methods of Testing," A. S. T. M. Designation E-6, and to the standard of the AMERICAN WELDING SOCIETY, entitled "Definitions of Welding Terms and Master Chart of Welding Processes." The term "soundness" used in this standard means the degree of freedom of a weld from defects discernible by visual inspection of any exposed surface of weld metal. In preparing reports of tests made in accordance with this standard, nomenclature shall conform to the above standards and definitions.

IV. Etching

Specimens to be tested in accordance with this standard shall be etched for either of two purposes: (1) to determine the soundness of a weld (see Sec. VI, *B*), or (2) to determine the location of a weld.

For tests in which the dimensions of the specimen, the procedure or the results depend upon the location of the weld, the surface of the specimen at and adjacent to the weld shall first be etched with any reagent which makes the boundary between the weld metal and the base metal visible, if the boundary is not already distinctly visible.

NOTE: Some reagents commonly used for carbon steels and low-alloy steels (5% or less of alloying elements) are the following:

Hydrochloric acid—Equal parts by volume of concentrated hydrochloric (muriatic) acid and water. Immerse the welds in this reagent at or near the boiling temperature. Hydrochloric acid will etch satisfactorily on unpolished surfaces. It will usually enlarge gas pockets and dissolve slag inclusions, enlarging the resulting cavities.

Ammonium persulphate—One part of ammonium persulphate (solid) to nine parts of water by weight. Vigorously rub the sur-

face of the weld with cotton saturated with this reagent at room temperature.

Iodine and potassium iodide—One part of powdered iodine (solid) to twelve parts of a solution of potassium iodide by weight. The solution should consist of one part of potassium iodide to five parts of water by weight. Brush the surface of the weld with this reagent at room temperature.

Nitric acid—One part of concentrated nitric acid to three parts of water by volume.

Caution—Always pour the acid into the water when diluting. Nitric acid causes bad stains and severe burns.

Either apply this reagent to the surface of the weld with a glass stirring rod at room temperature, or immerse the weld in boiling reagent provided the room is well ventilated. Nitric acid etches rapidly. It should be used on polished surfaces only, and will show the refined zone as well as the weld metal zone.

After etching, the weld should immediately be washed in clear water, preferably hot water; the excess water should be removed; the etched surface should then be immersed in ethyl alcohol, removed and dried, preferably in a warm air blast. The appearance may be preserved by coating with a thin clear lacquer.

DETAILS OF TESTS

V. Base Metal

If there are specifications for the base metal, the tests of the base metal shall be in accordance with these specifications.

If there are no specifications for the base metal, the tests of the base metal shall be carried out in accordance with the standards of the American Society for Testing Materials. Tensile tests, if any, shall be in accordance with "Standard Methods of Tension Testing of Metallic Materials," A. S. T. M. Designation E-8.

VI. Weld Metal

A. Density

1. *Specimen.*—The specimen, *A*, shall be a cylinder complying with the requirements of Fig. 1, and consisting entirely of metal from the deposited metal zone. If the size of the weld is insufficient, the specimen may be machined from a test plate complying with the requirements of Fig. 2.

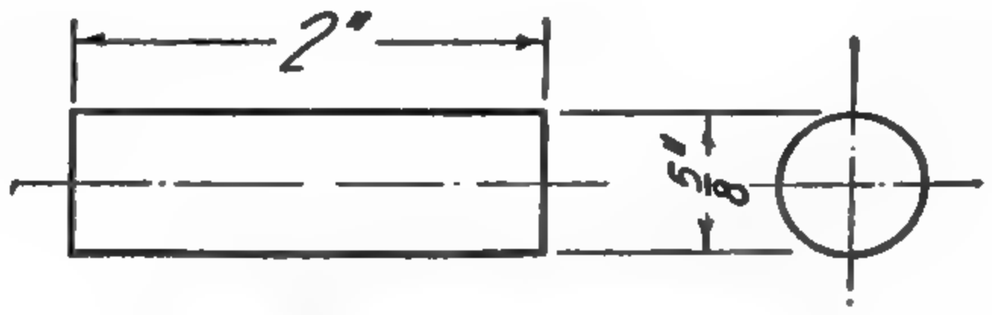


Fig. 1—Density Specimen *A*

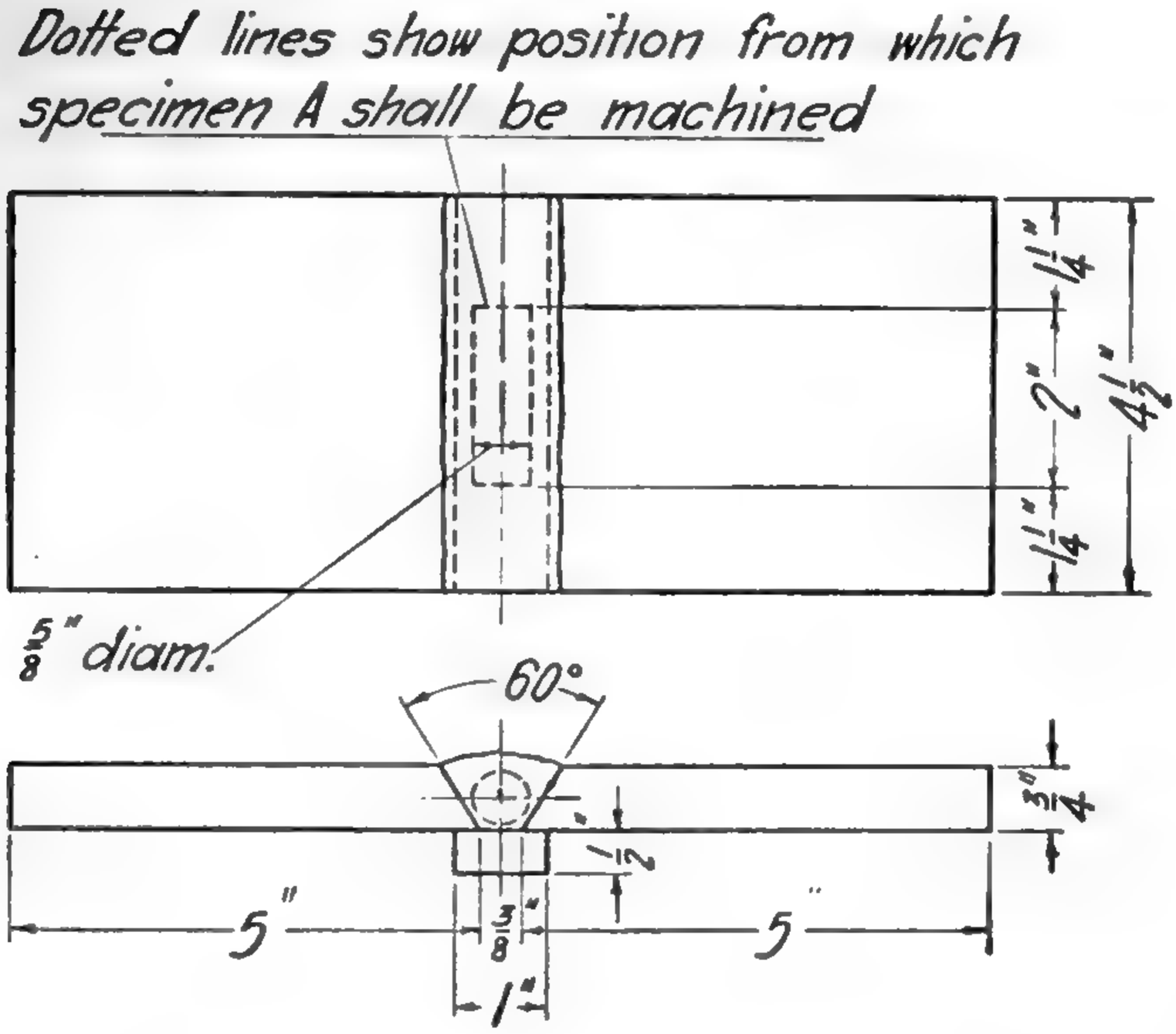


Fig. 2—Test Plate for Density Specimen *A*

2. *Procedure.*—After the specimen has been subjected to room temperature for not less than two hours, the average dimensions shall be measured (screw micrometer) to the nearest 0.0001 inch and the room temperature in degrees Centigrade shall be determined. Using a balance having an error not exceeding 0.0001 gm., the weight of the specimen in air shall be determined.

3. *Results.*—The density shall be computed using the formula:

$$\text{Density, in grams per cubic centimeter} = \frac{\text{weight in air, in grams}}{\text{volume in cubic inches} \times (1 - 0.000033 \times t) \times 16.3872}$$

in which

t = temperature of specimen in degrees Centigrade.
16.3872 = number of cubic centimeters in one cubic inch.
0.000033 = volumetric coefficient of expansion of ferrous weld metal per degree Centigrade.

NOTE: The density is not an accurate measure of the soundness of weld metal. Voids or slag inclusions, scattered throughout the metal abundantly enough so that on an average straight line scribed on the face of the metal, one-twentieth of the length strikes voids, would result in a change in density of $(1/20)^3$ or one in 8000 (0.012%). To detect such a change calls for high accuracy of measurement. A further difficulty rises from the fact that the normal variations in density between different lots of sound steel may be themselves much greater than one in 8000.

B. Soundness: Etch Test[1]

1. *Specimen.*—A portion of the joint, specimen *B* (no figure) displaying a complete transverse section of the weld shall be removed by any convenient means such as trepanning, flame cutting, drilling or sawing. If removed by flame cutting at least $^1/_8$ inch shall be machined from the face that sections the weld. This face shall be smooth, bright and polished.

NOTE: The face may be filed and polished with abrasive cloth finishing with grade 00.

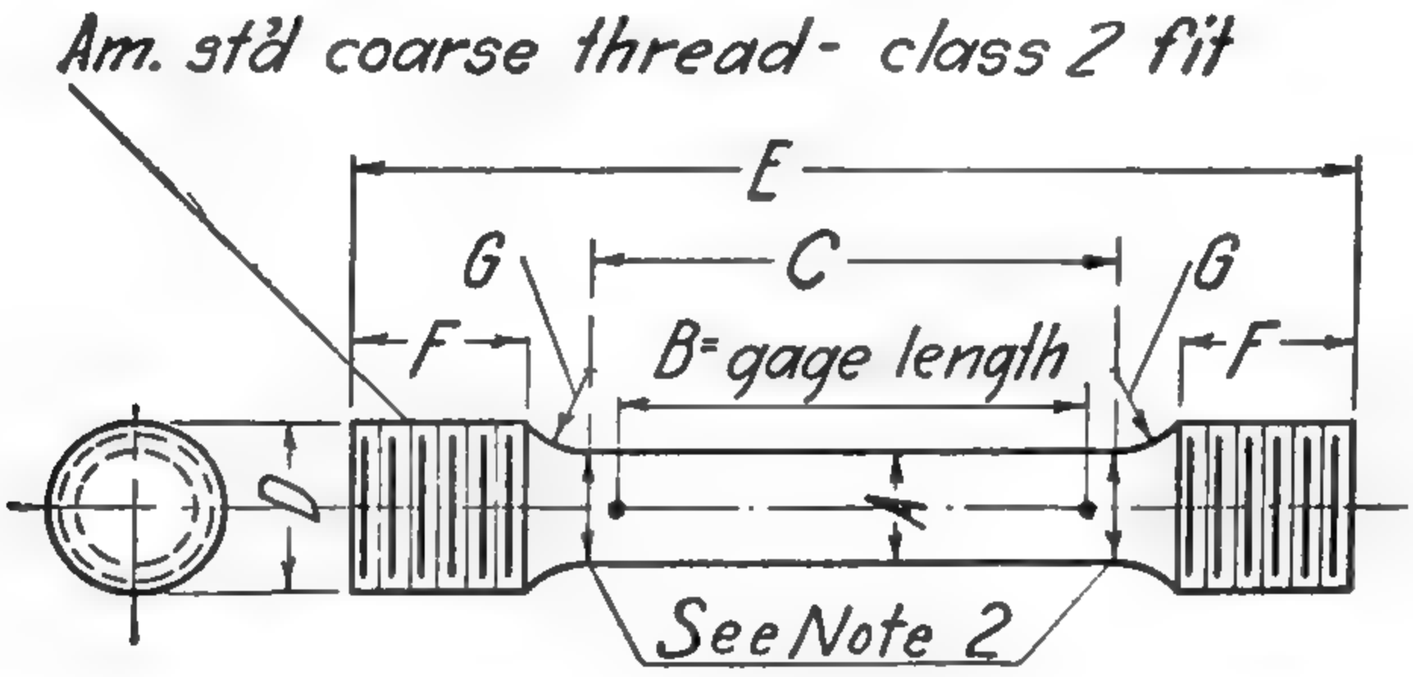
2. *Procedure.*—The face shall be etched. (See Note, Section IV, for suggested etching reagents.)

3. *Results.*—The etched transverse section of the weld shall be examined for soundness. (See Sec. III.)

NOTE: Persons writing codes or specifications should state definitely their requirements for soundness. Typical requirements are: "complete penetration," "no inclusions," "the number of gas pockets shall not exceed——per square inch," "no gas pocket shall exceed——inches in its greatest dimension," etc.

C. Tensile Strength

1. *Specimen.*—The specimen shall comply with the requirements of Fig. 3, specimen *C*-1 being used unless the size of the welded joint or deposited weld metal is such that a specimen of this size cannot be ma-



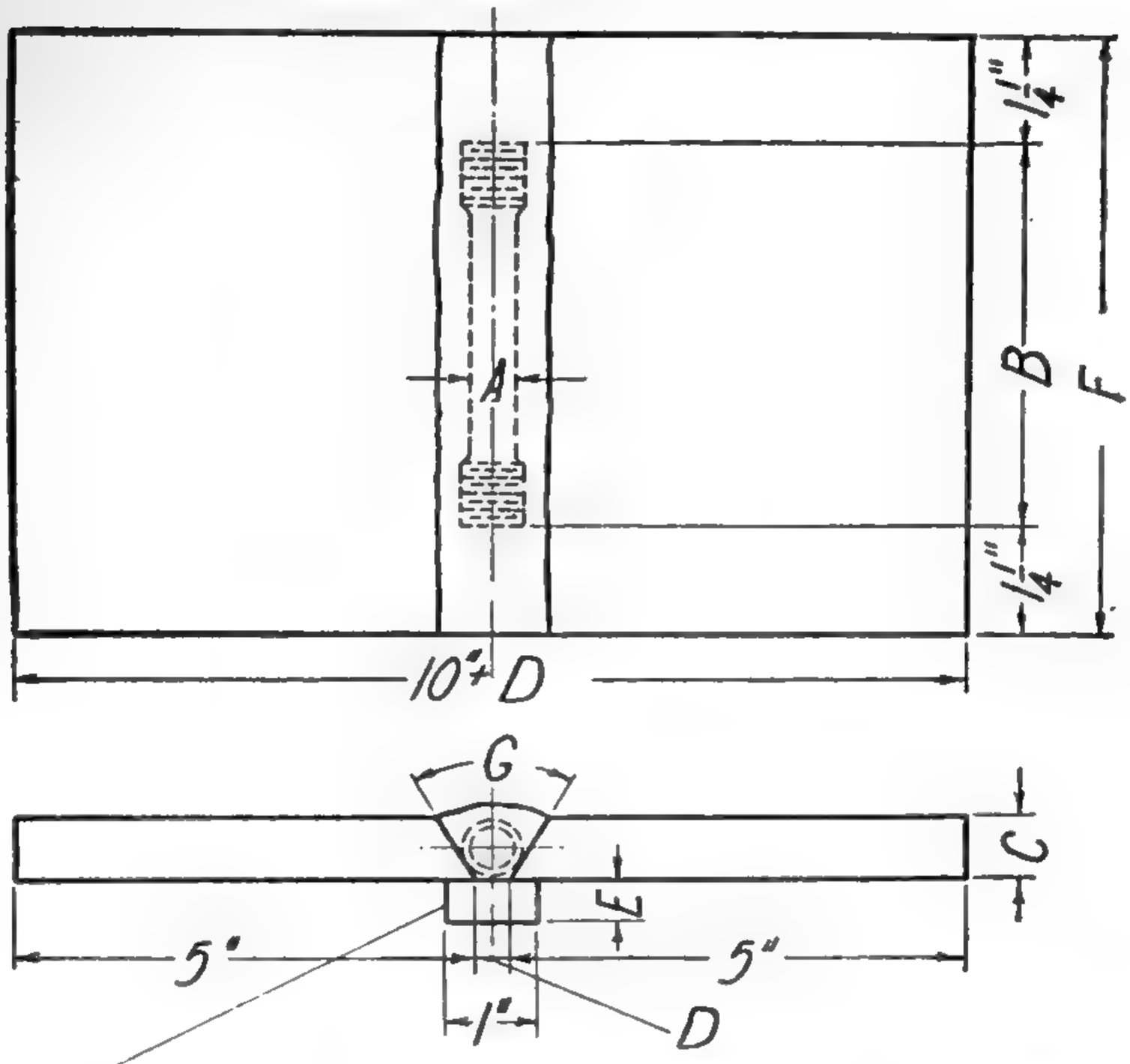
Specimen	Dimensions of Specimen						
	A, In.	B, In.	C, In.	D, In.	E, In.	F, In.	G, In., Min.
C-1	0.500 ± 0.01	2	$2^1/_4$	$^3/_4$	$4^1/_4$	$^3/_4$	$^3/_8$
C-2	0.437 ± 0 01	$1^3/_4$	2	$^5/_8$	4	$^3/_4$	$^3/_8$
C-3	0.357 ± 0.007	1.4	$1^3/_4$	$^1/_2$	$3^1/_2$	$^5/_8$	$^3/_8$
C-4	0.252 ± 0.005	1.0	$1^1/_4$	$^3/_8$	$2^1/_2$	$^1/_2$	$^1/_4$
C-5	0.126 ± 0.003	0.5	$^3/_4$	$^1/_4$	$1^3/_4$	$^3/_8$	$^1/_8$

Note 1: Dimension A, B and C shall be as shown, but alternate shapes of ends may be used as allowed by ASTM Specification *E*-8

Note 2: It is desirable to have the diameter of the specimen within the gage length slightly smaller at the center than at the ends. The difference shall not exceed 1 per cent of the diameter.

Fig. 3—All-Weld-Metal Tension Specimens *C*-1 to *C*-5, Inclusive

[1] See also Sections VII*A* and VIII*A*.



For gas welding, backing strip shall be omitted.
Dotted lines show position from which
specimen shall be machined.

Welding Process	Diameter of Electrode or Welding Rod, In.	Specimen	Dimensions of Test Plate and Tension Test Specimens						
			A, In.	B, In.	C, In.	D, In.	E, In.	F, In.	G, Deg.
Arc	Under 5/32	C-4	0.252 ± 0.005	2 1/2	1/2	1/4	3/16	5	45
"	5/32 to 7/32	C-1	0.500 ± 0.01	4 1/4	3/4	1/2	1/4	6 3/4	45
"	1/4	C-1	0.500 ± 0.01	4 1/4	1	1/2	1/2	6 3/4	45
"	5/16	C-1	0.500 ± 0.01	4 1/4	1 1/4	1/2	1/2	6 3/4	45
"	3/8	C-1	0.500 ± 0.01	4 1/4	1 1/2	1/2	1/2	6 3/4	45
Gas	Under 3/16	C-4	0.252 ± 0.005	2 1/2	3/8 min.	1/8		5	75
"	3/16 and over	C-1	0.500 ± 0.01	4 1/4	3/4 min.	1/4		6 3/4	75

Note: Test plate may be lengthened as desired to provide for more than one specimen.

Fig. 4—Test Plate for All-Weld-Metal Tension Specimen C-1 or C-4

chined from it. In the latter case, specimens *C*-2, *C*-3, *C*-4 or *C*-5 shall be used, choosing the specimen having the largest diameter which can be machined from the material to be tested. The portion of the specimen included in the gage length *B* shall consist entirely of metal from the deposited metal zone. All of these specimens are geometrically similar in all significant dimensions, therefore the properties determined from any one of them tend to be approximately the same as the properties determined from any other one. However, it is desirable that comparisons be made only between specimens of the same size.

In the event that filler metal is to be deposited specifically for the purpose of this test, test plates and specimens complying with the requirements of Fig. 4 shall be used. The apparatus, materials, methods and rate of depositing the weld metal in the test plate shall, so far as practicable, be the same as those used in making welds with the given filler metal.

NOTE: Due to unavoidable differences in the method of depositing the filler metal and in rates of cooling, the properties of the weld metal determined from a specimen will depend upon the dimensions of the adjacent metal.

For thermit welds a suitable refractory material shall be used for a trough in which the weld metal is to be allowed to solidify.

2. *Procedure.*—The diameter of the specimen at the middle of the reduced section shall be measured in inches and the gage length defined by a gage mark at each end. The specimen shall be ruptured under tensile load, and the maximum load in pounds shall be determined.

3. *Results.*—The tensile strength shall be obtained in pounds per sq. in., by dividing the maximum load by the cross-sectional area of the specimen at the middle. The cross-sectional area of the specimen shall be obtained by squaring the diameter of the specimen and multiplying by 0.785. The elongation shall be determined by removing the specimen from the machine, fitting the fractured ends of the specimen together, measuring the distance between the gage marks and subtracting the gage length. The per cent elongation shall be obtained by dividing the elongation by the gage length and multiplying by 100.

VII. Welded Butt Joints

General Statement: Individual specifications may designate which of the specimens described in this section shall be used, and the order in which they shall be cut from any prepared plate or pipe sample. No weld in a plate sample shall be begun or ended nearer than one inch to any portion of a welded specimen taken from that plate.

A. Soundness: Nick-Break Test

1. *Specimen.*—For a welded butt joint in plate, the nick-break specimen, *D*-1, shall comply with the requirements of Fig. 5.

For a welded butt joint in pipe or tubing the nick-break specimen, *D*-2, shall comply with the requirements of Fig. 6.

2. *Procedure.*—The specimen shall be supported substantially in accordance with Fig. 7 and ruptured by a force which, unless otherwise specified, may be applied either slowly or suddenly as by one or more blows of a hammer.

NOTE: A sharp sudden heavy blow is often specified. There appears to be but little evidence to indicate that there is any appreciable difference in the appearance of the fractured surface caused by a difference in the rate of applying the force.

3. *Results.*—The surfaces of the fracture shall be examined for soundness. (See Sec. III and Note, Sec. VI, *B* 3.)

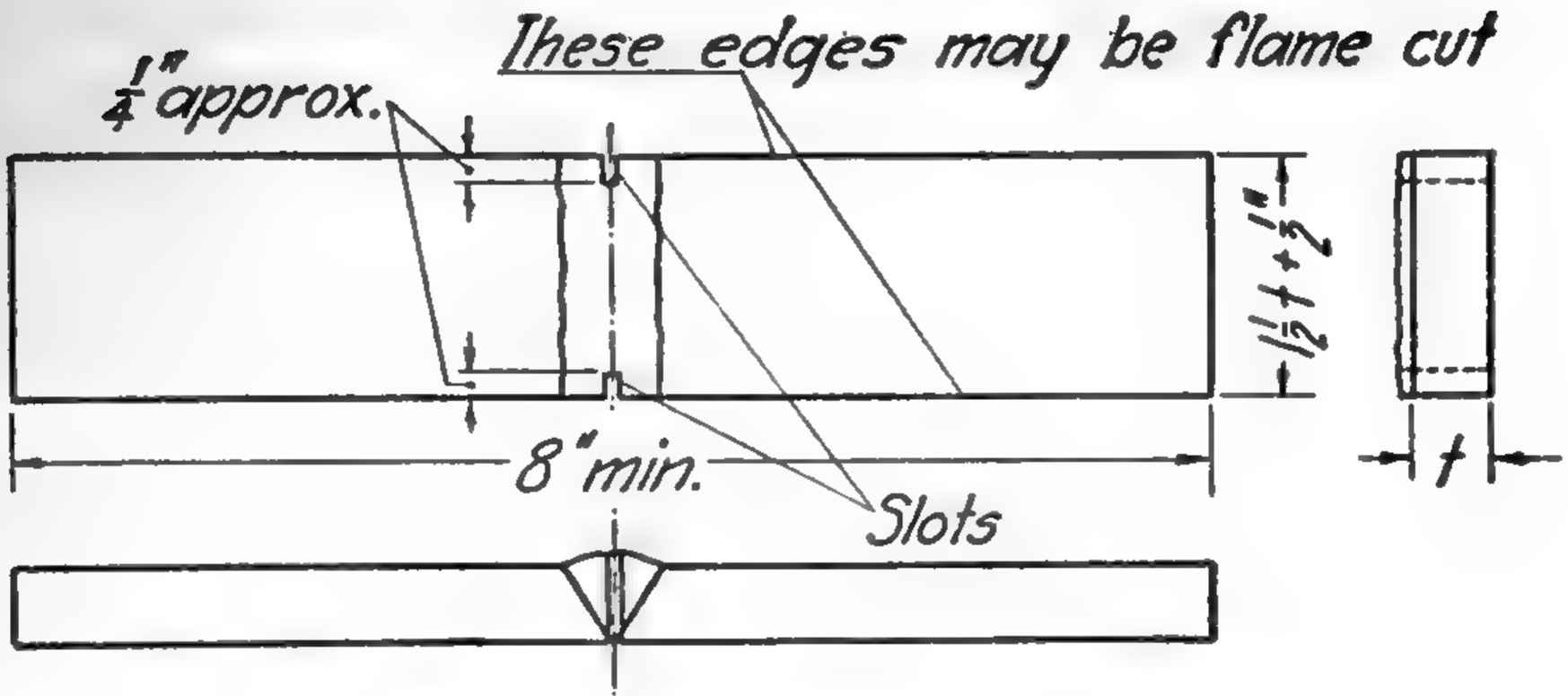


Fig. 5—Nick-Break Specimen *D*-1 (Plate)

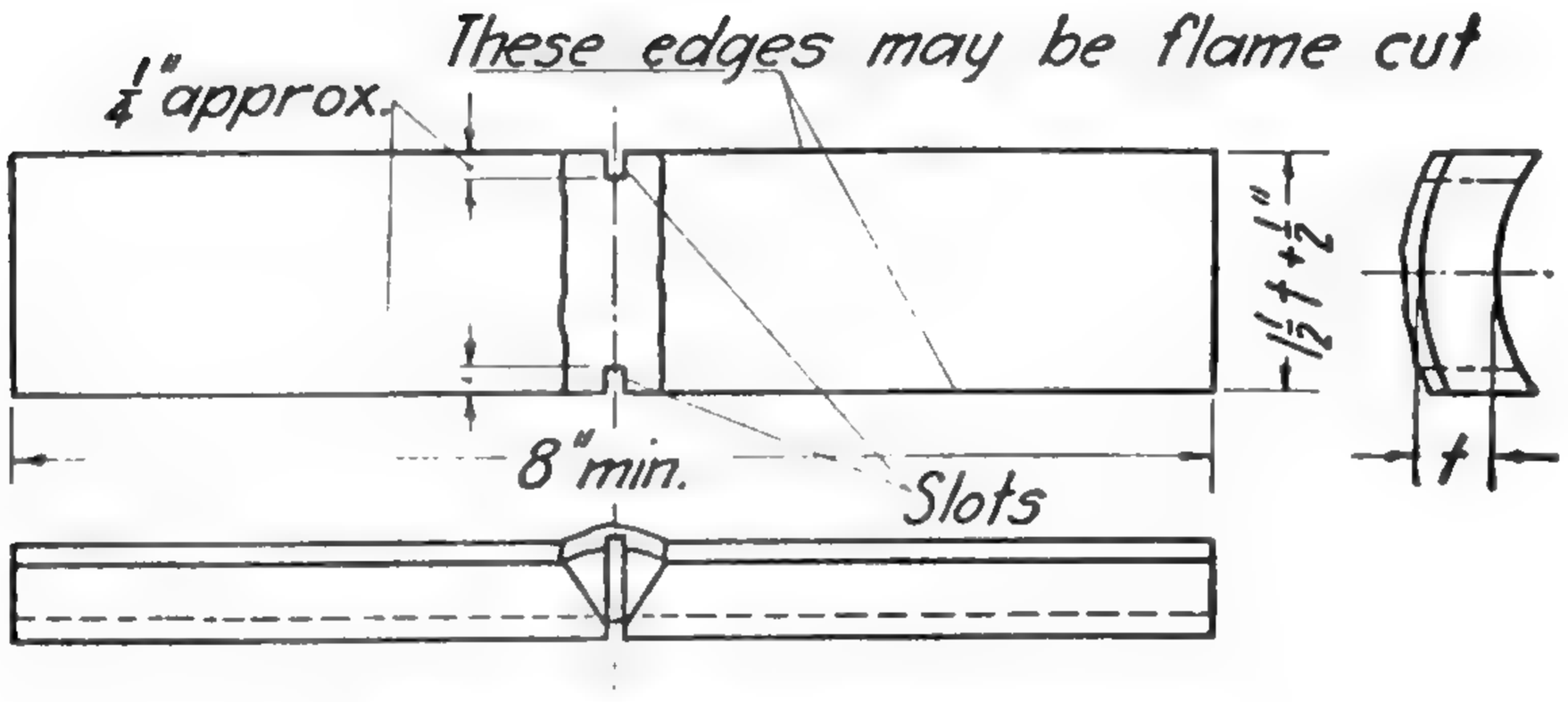


Fig. 6—Nick-Break Specimen *D*-2 (Plate

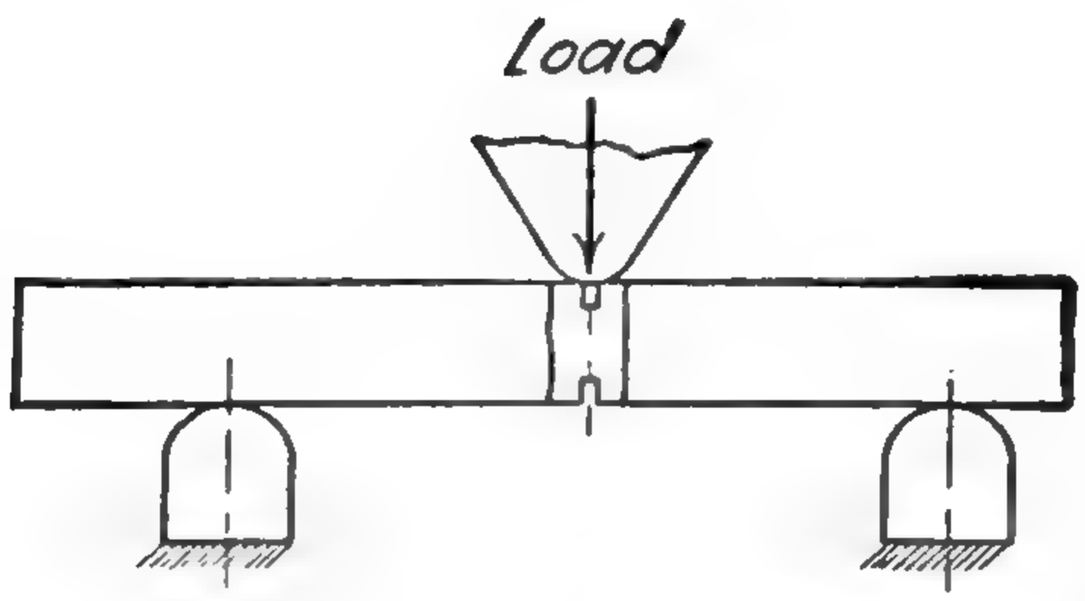


Fig. 7—Method of Rupturing Nick-Break Specimens

B. Soundness: Guided-Bend Test

1. *Specimens.*—For welded butt joints in plate, the face-bend specimen, *E*-1, and the root-bend specimen, *F*-1, shall comply with the requirements of Fig. 8.

For welded butt joints in pipe or tubing, the face-bend specimen, *E*-2, and the root-bend specimen, *F*-2, shall comply with the requirements of Fig. 9.

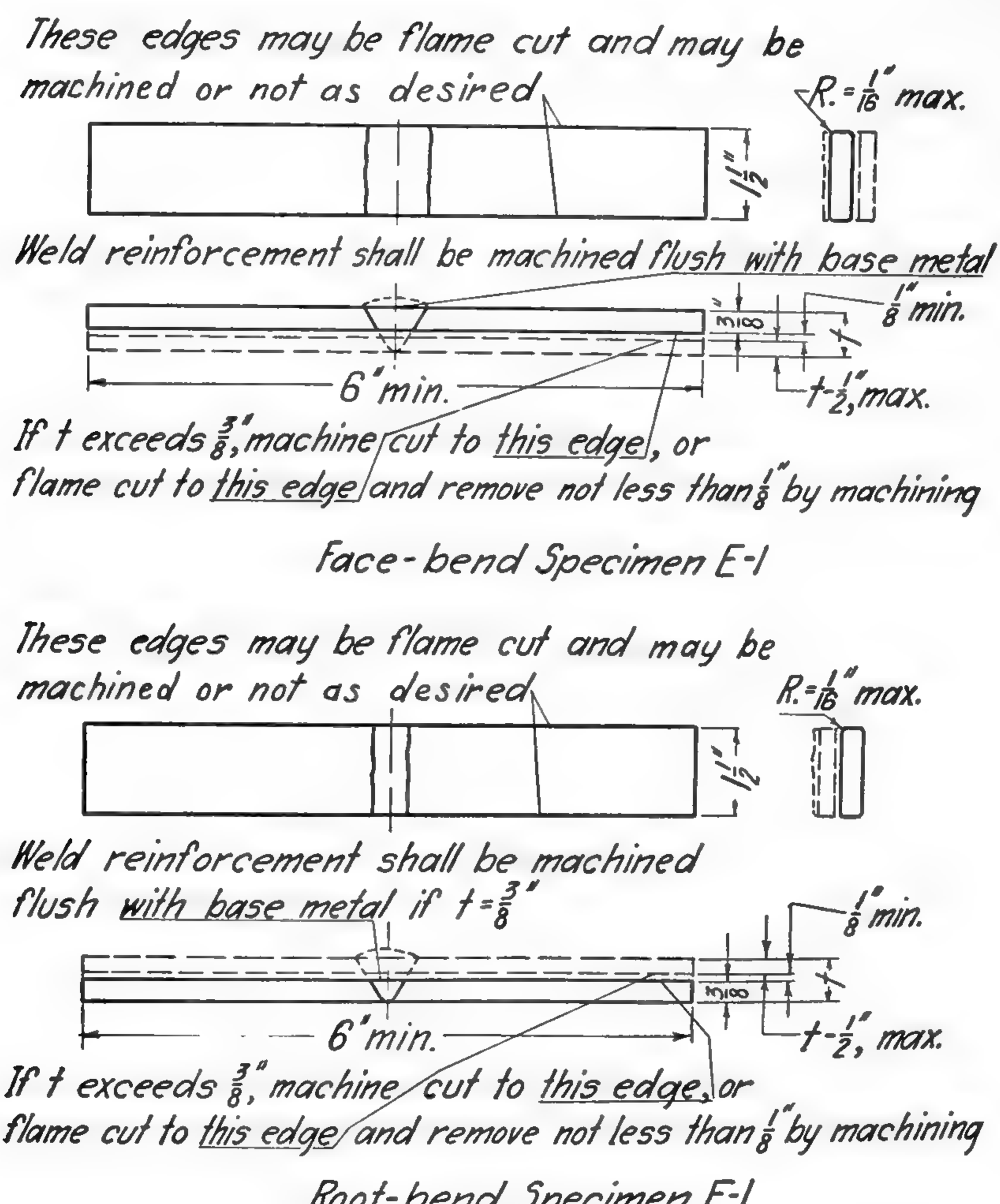
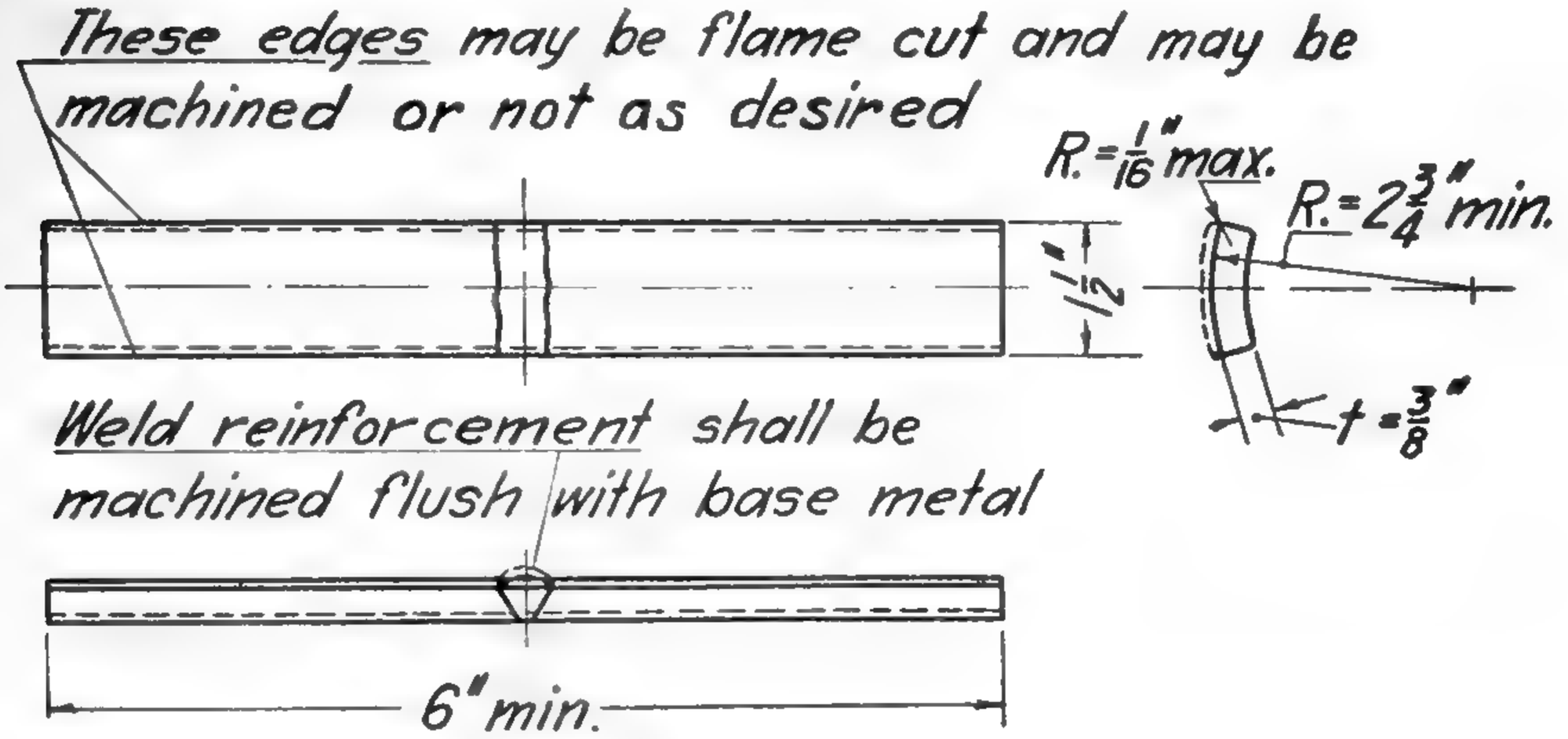


Fig. 8—Face- and Root-Bend Specimens E-1 and F-1 (Plate)

The side-bend specimen, *G*, shall comply with the requirements of Fig. 10.

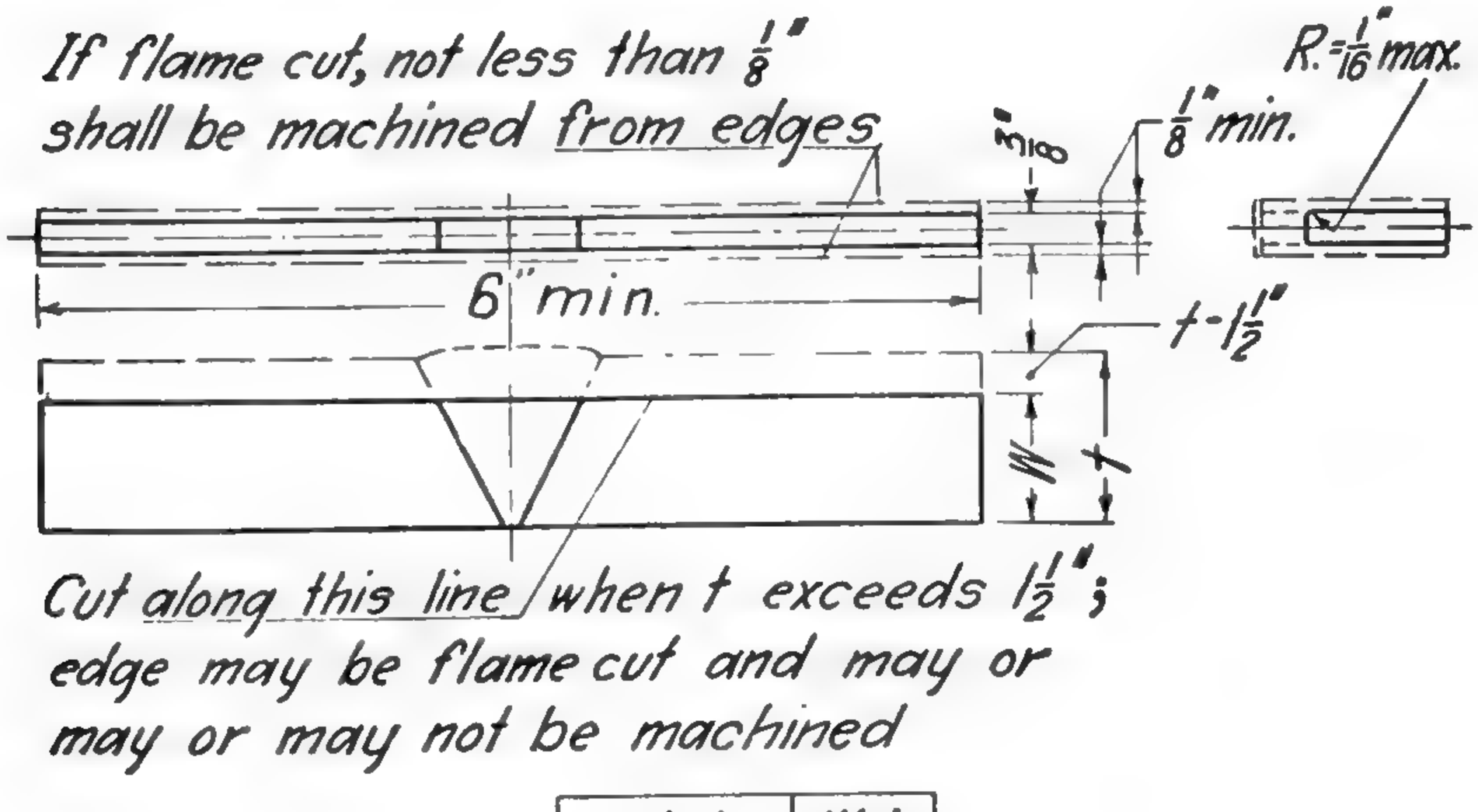
Tool marks, if any, shall be lengthwise of the specimen.

NOTE: Tests have shown that the severity of the guided-bend test increases to some extent with increasing width/thickness ratio of the



Note: This test as now specified is intended for pipe of 3/8-inch nominal wall thickness only, and is not considered suitable for pipe having a nominal diameter of less than 6 inches.

Fig. 9—Face- or Root-Bend Specimens, *E*-2 or *F*-2, Respectively (Pipe)



t, in.	W, in.
3/4" to 1 1/2"	t
> 1 1/2"	1 1/2"

Note: The side-bend test is not applicable if the plate thickness (t) is less than 3/4 inch.

Fig. 10—Side-Bend Specimen G

specimen. Results of the side-bend test are therefore not directly comparable when obtained on specimens *G*, Fig. 10, having different widths *W*.

2. *Procedure.*—Each specimen shall be bent in a jig having the working contour shown in Fig. 11, and otherwise substantially in accordance with that figure. Any convenient means may be used for moving the plunger member with relation to the die member.

The specimen shall be placed on the die member of the jig with the weld at midspan. Face-bend specimens, *E*-1 and *E*-2, shall be placed with the face of the weld directed toward the gap; root-bend specimens, *F*-1 and *F*-2, shall be placed with the root of the weld directed toward the gap; side-bend specimen, *G*, shall be placed with that side showing the greater defects, if any, directed toward the gap. The two members of the jig shall be forced together until the specimen conforms to a U-shape, and until a $^{1}/_{32}$-in. diameter wire cannot be placed between the specimen and any point on the curvature of the plunger member of the jig. The specimen shall then be removed from the jig.

3. *Results.*—The convex surface of the specimen shall be examined for the appearance of cracks or other open defects Any specimen in which a crack or other open defect is present after the bending, exceeding a specified size measured in any direction, shall be considered as having failed. Cracks occurring on the corners of the specimen during testing shall not be considered unless they exceed a similarly specified size.

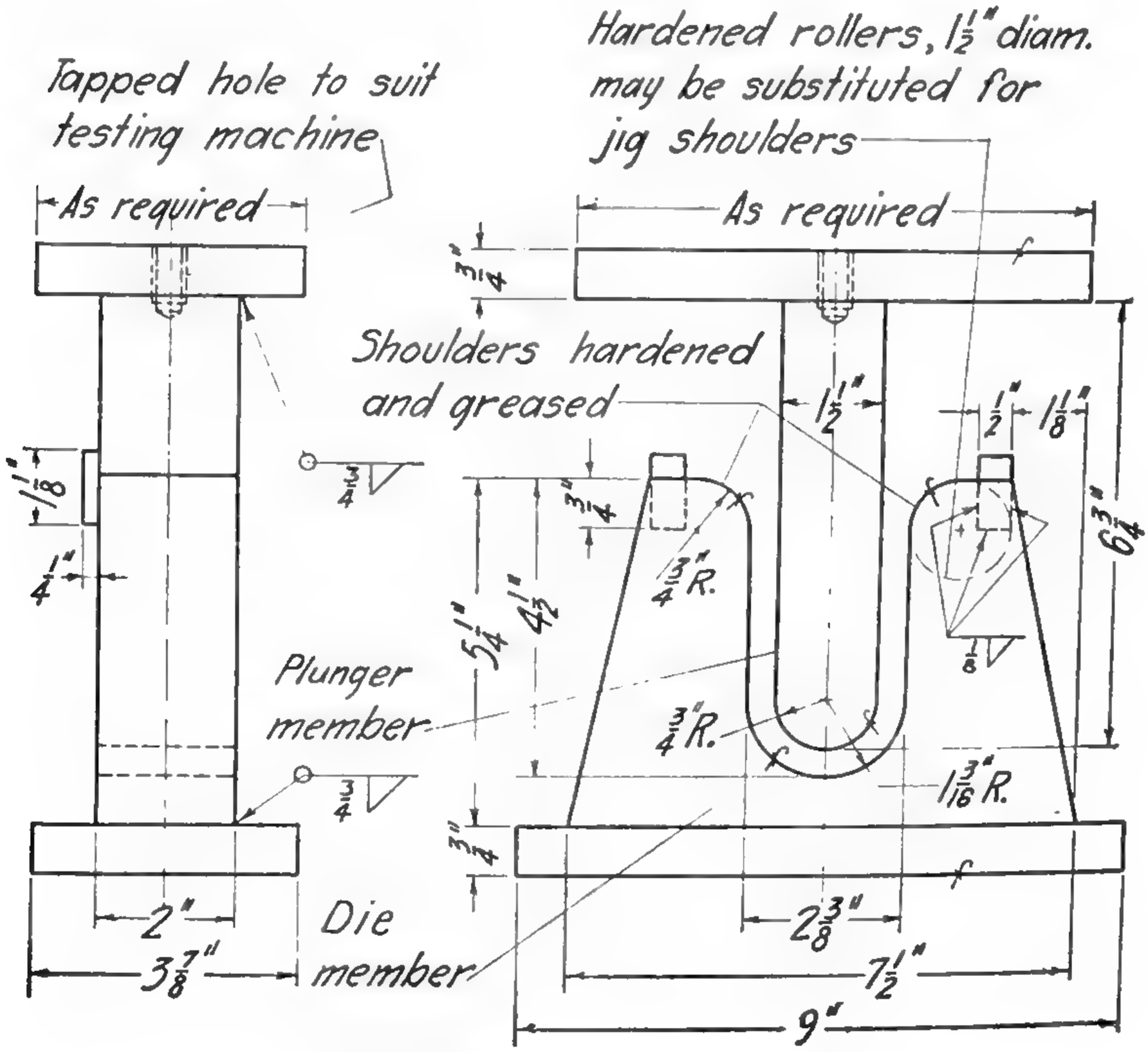


Fig. 11—Guided-Bend Test Jig

C. Tensile Strength

1. *Specimens.*—For a welded butt joint in plate, the tension specimen *H*-1 shall comply with the requirements of Fig. 12.

For a circumferentially-welded butt joint in pipe or tubing having a nominal diameter exceeding 2 inches, either specimen *H*-2 or *H*-3 may be used as called for in the code or specification. Specimen *H*-2 shall comply with the requirements of Fig. 13. The ends of the specimen may either be

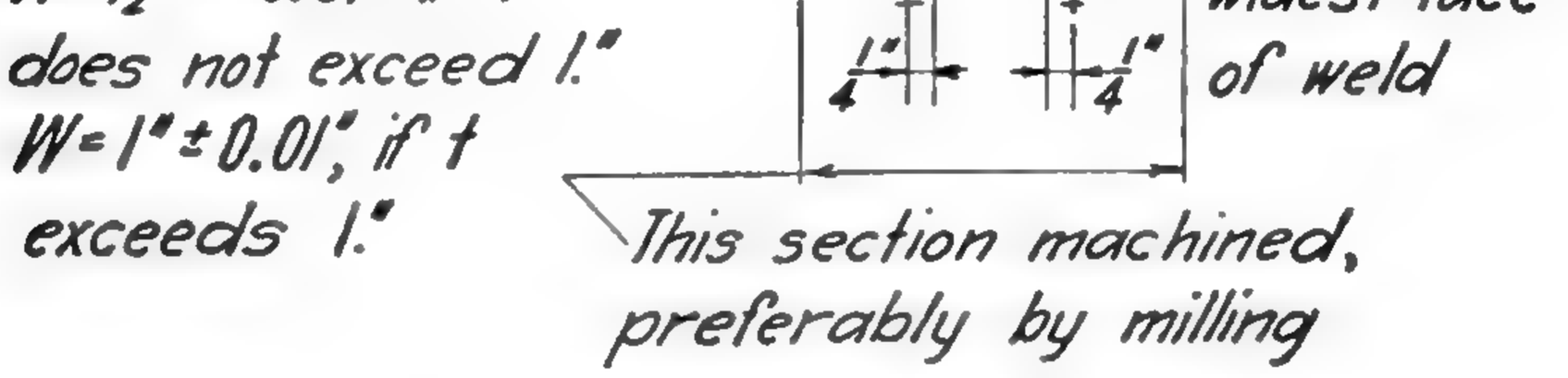


Fig. 12—Tension Specimen *H*-1 (Plate)

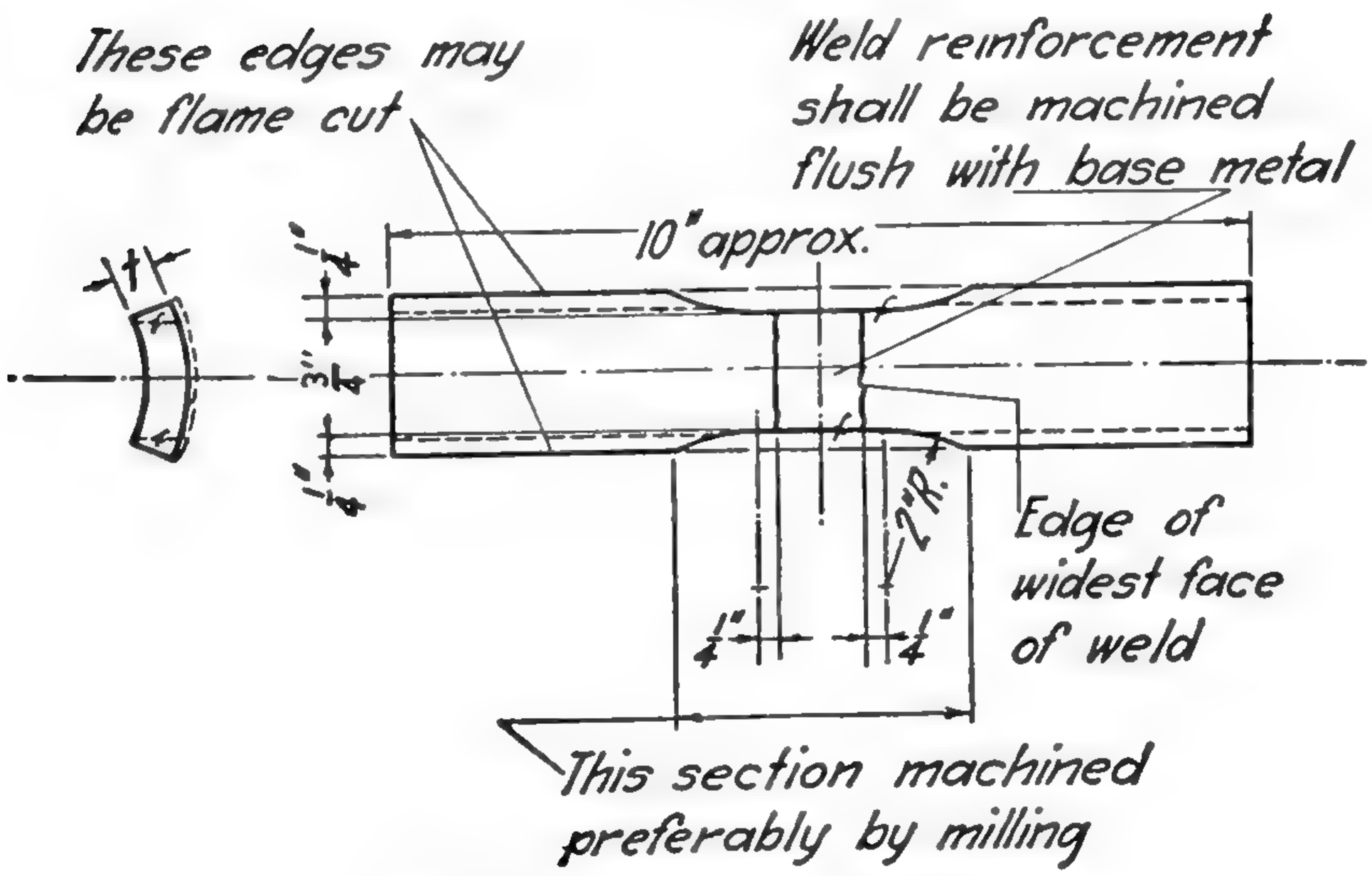


Fig. 13—Tension Specimen *H*-2 (Pipe)

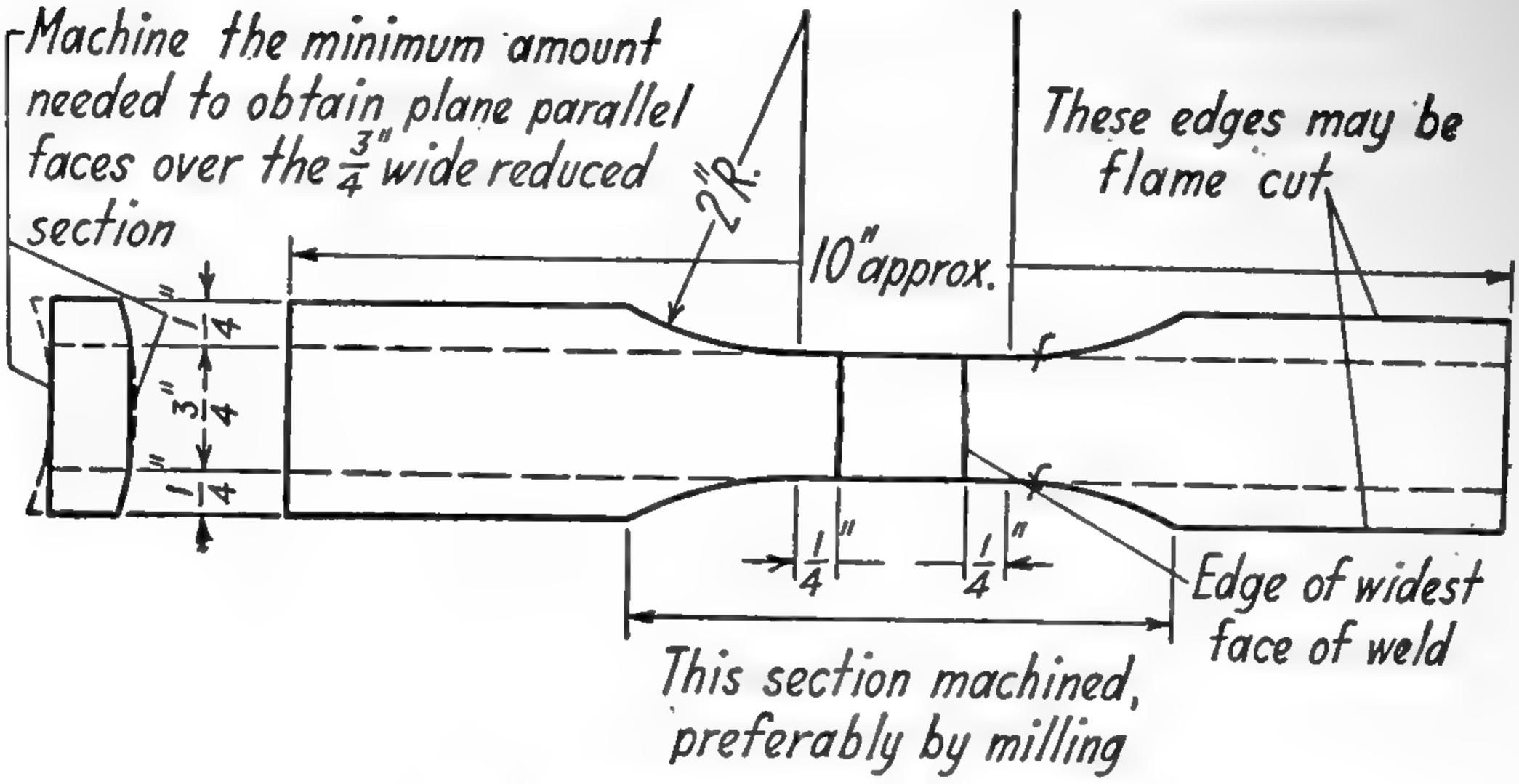


Fig. 14—Tension Specimen *H*-3 (Pipe)

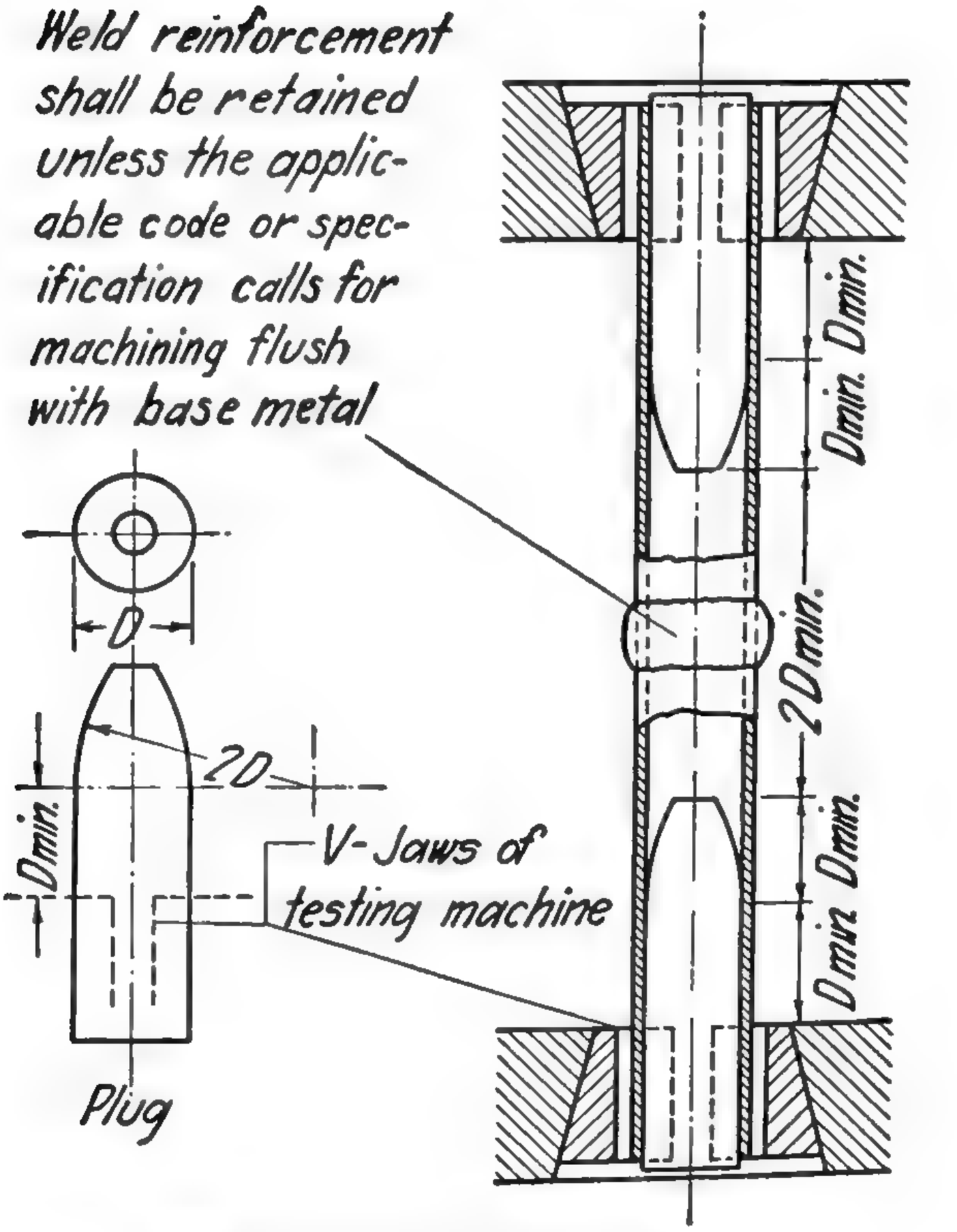


Fig. 15—Tension Specimen *H*-4 (Pipe)

flattened by any suitable means or the ends may be placed in the grips of the testing machine without flattening. Specimen *H*-3 shall comply with the requirements of Fig. 14. This specimen is not recommended for wall thicknesses less than $^3/_8$ inch nominal.

For circumferentially-welded butt joints in pipe or tubing having a nominal diameter not exceeding 2 inches, the specimen *H*-4 (full section specimen) shall comply with the requirements of Fig. 15.

2. *Procedure.*—For specimens *H*-1, *H*-2 and *H*-3, the least width and corresponding thickness of the reduced section shall be measured in inches. For specimen *H*-4, the average outside diameter, *O.D.*, of the base metal at a distance not exceeding $^1/_2$ inch from the boundary between the base metal and the weld metal, and also the average inside diameter, *I.D.*, of the base metal at either end of the specimen shall be measured in inches. The specimen shall be ruptured under tensile load and the maximum load in pounds shall be determined.

3. *Results.*—The cross-sectional area shall be obtained as follows:

Specimen	*Cross-Sectional Area* =
H-1, *II*-2 or *H*-3	width × thickness
II-4	0.785 ($O.D.^2 - I.D.^2$)

The *tensile strength* in pounds per sq. in. shall be obtained by dividing the maximum load by the cross-sectional area.

D. Ductility: Free-Bend Test

1. *Specimen.*—For welded butt joints in plate, the specimen, *J*-1, shall comply with the requirements of Fig. 16.

For a circumferentially-welded butt joint in pipe or tubing, the specimen, *J*-2, shall comply with the requirements of Fig. 17.

In both cases the width shall be 1.5 multiplied by the thickness of the specimen. Each corner lengthwise of the specimen shall be rounded in a radius not exceeding $^1/_{10}$ the thickness (t) of the specimen. Tool marks, if any, shall be lengthwise of the specimen.

If the line between the weld metal and the base metal is not distinctly visible when the specimen is ready for testing, the surface of the specimen shall be etched with a suitable reagent.

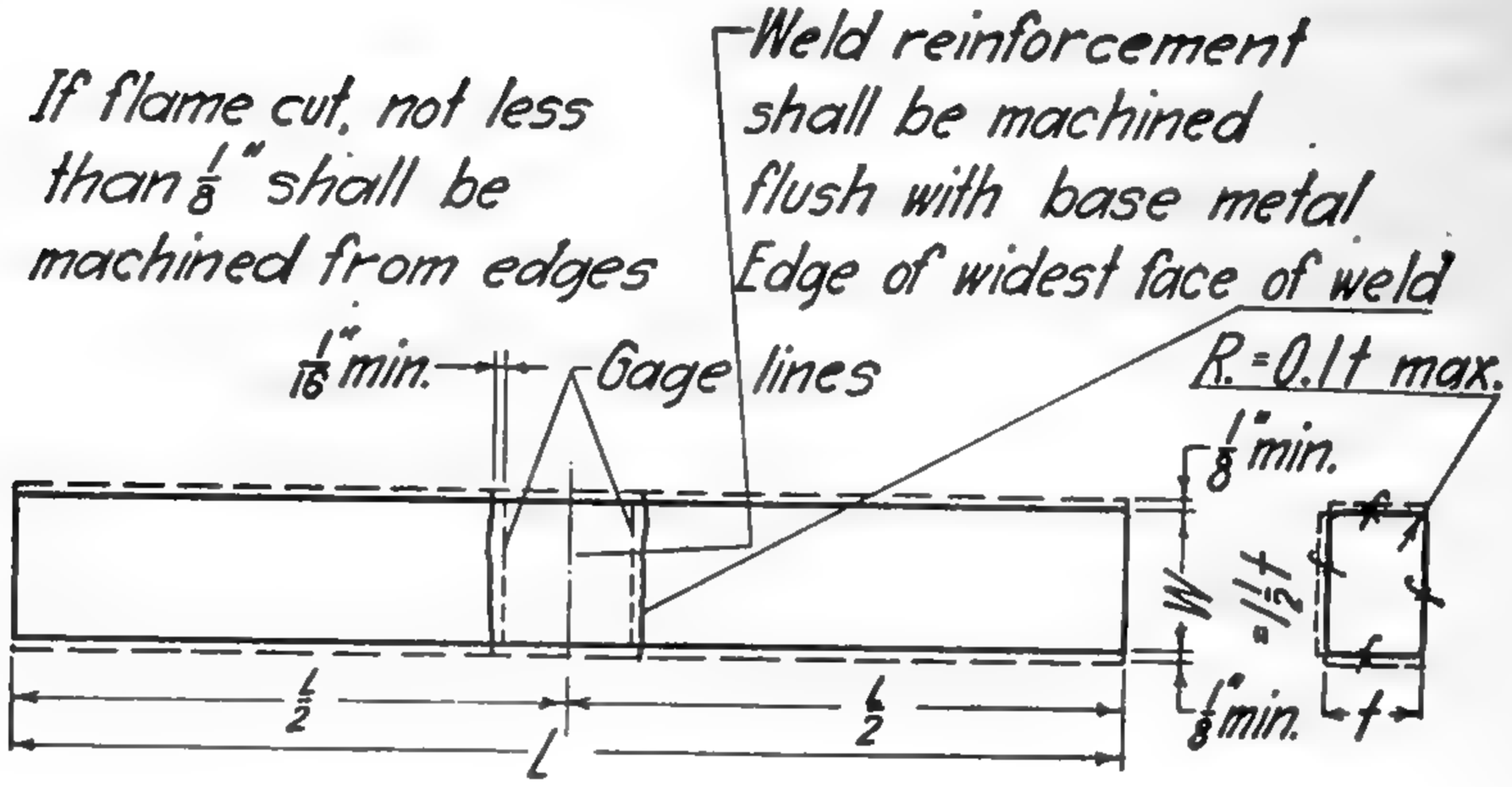
2. *Procedure.—Gage Lines:* The gage lines shall be lightly scribed on the face of the weld. The gage length (distance between gage lines) shall be approximately $^1/_8$ inch less than the width of the face of the weld, and shall be measured in inches to the nearest 0.01 inch.

For single groove welds, the gage lines shall be on the wider face of the weld.

For double groove welds, the gage lines on one-half the specimens shall be on one face of the weld, and on the other half of the specimens, on the other face.

Initial Bend: Each specimen shall be bent initially by the use of a device complying with the requirements of Fig. 18. The surface of the specimen containing the gage line shall be directed toward the supports. The weld shall be at midspan of both the supports and the loading block.

Alternate Initial Bend: If the purchaser and the vendor agree, the initial bend may be made by holding each specimen in the jaws of a vise with one-third the length of the specimen projecting from the jaws, then bending



Dimensions

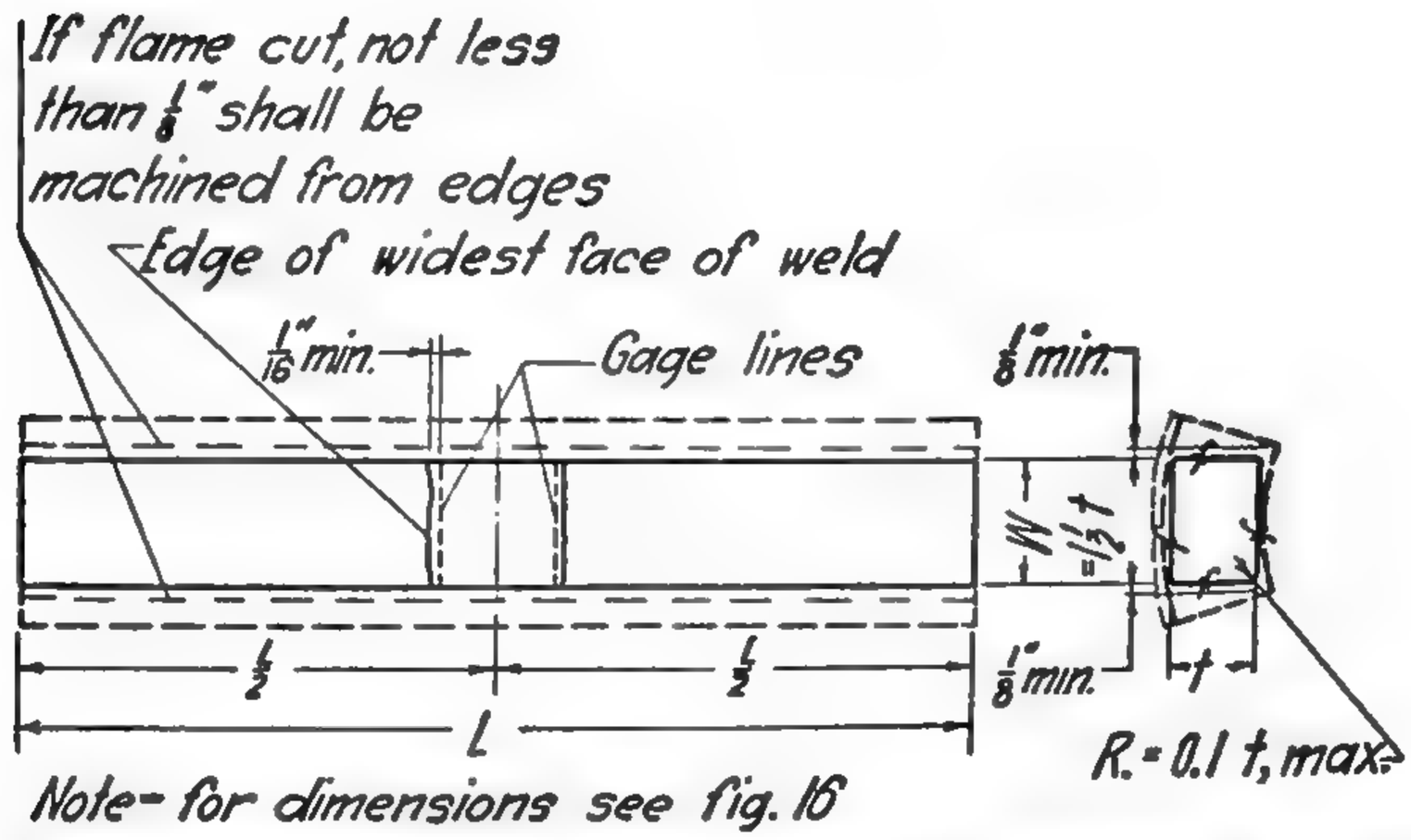
t, in.	1/4	3/8	1/2	5/8	3/4	1	1 1/4	1 1/2	2	2 1/2
W, in.	3/8	9/18	3/4	15/16	1 1/8	1 1/2	1 7/8	2 1/4	3	3 3/4
L min, in.	6	8	9	10	11	12	13 1/2	15	18	21
B* min, in.	1 1/4	1 1/4	1 1/4	2	2	2	2	2	2	3

*See fig. 18

Note:- the length L is suggestive only, not mandatory

Note: If desired, the edges of the specimen may be prepared by machine flame cutting, followed by rounding of the corners with a file, though this may be a more severe test.

Fig. 16—Free-Bend Specimen J-1 (Plate)



Note: If desired, the edges of the specimen may be prepared by machine flame cutting, followed by rounding of the corners with a file, though this may be a more severe test.

Fig. 17—Free-Bend Specimen J-2 (Pipe)

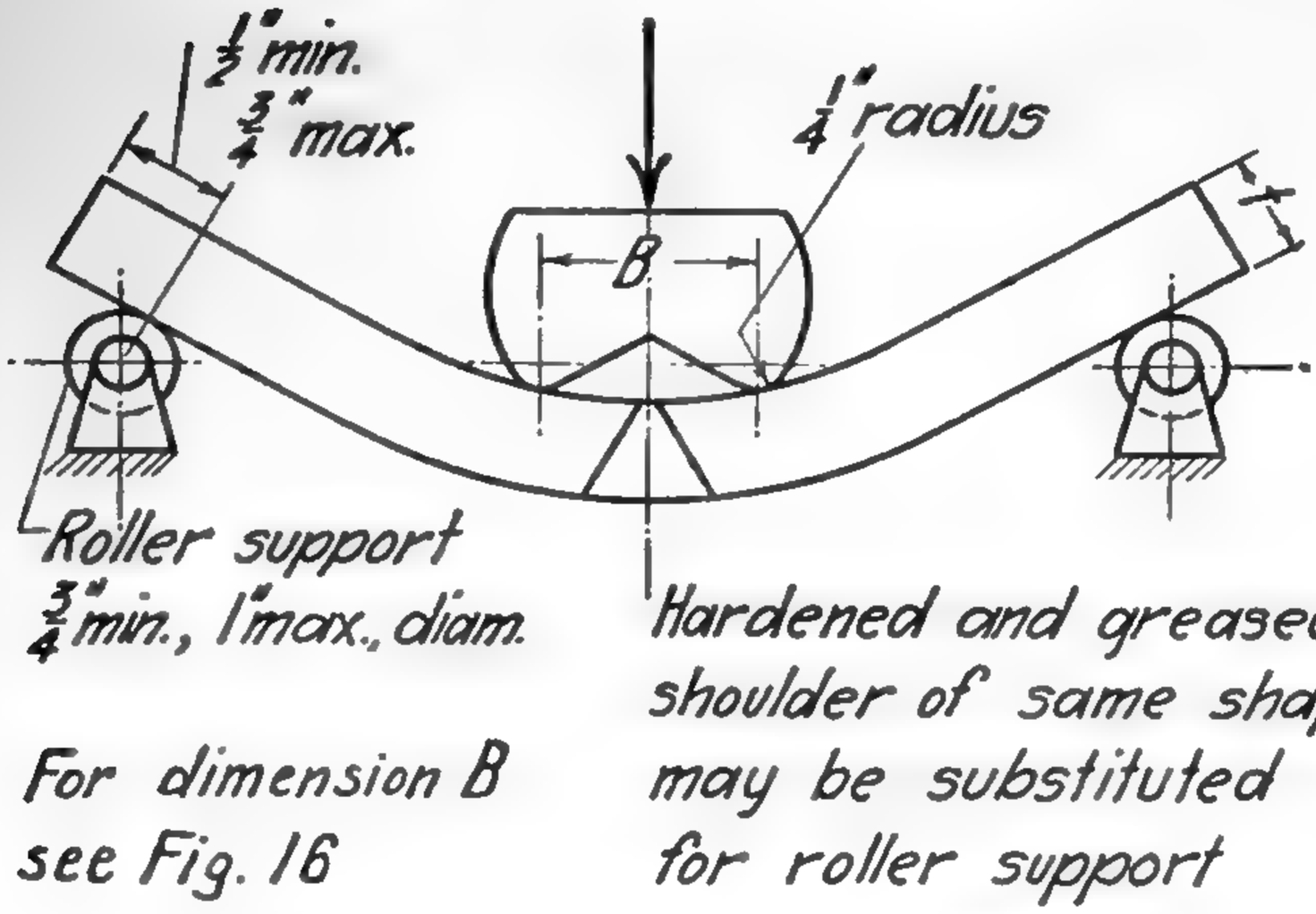


Fig. 18—Initial Bend for Free-Bend Specimens

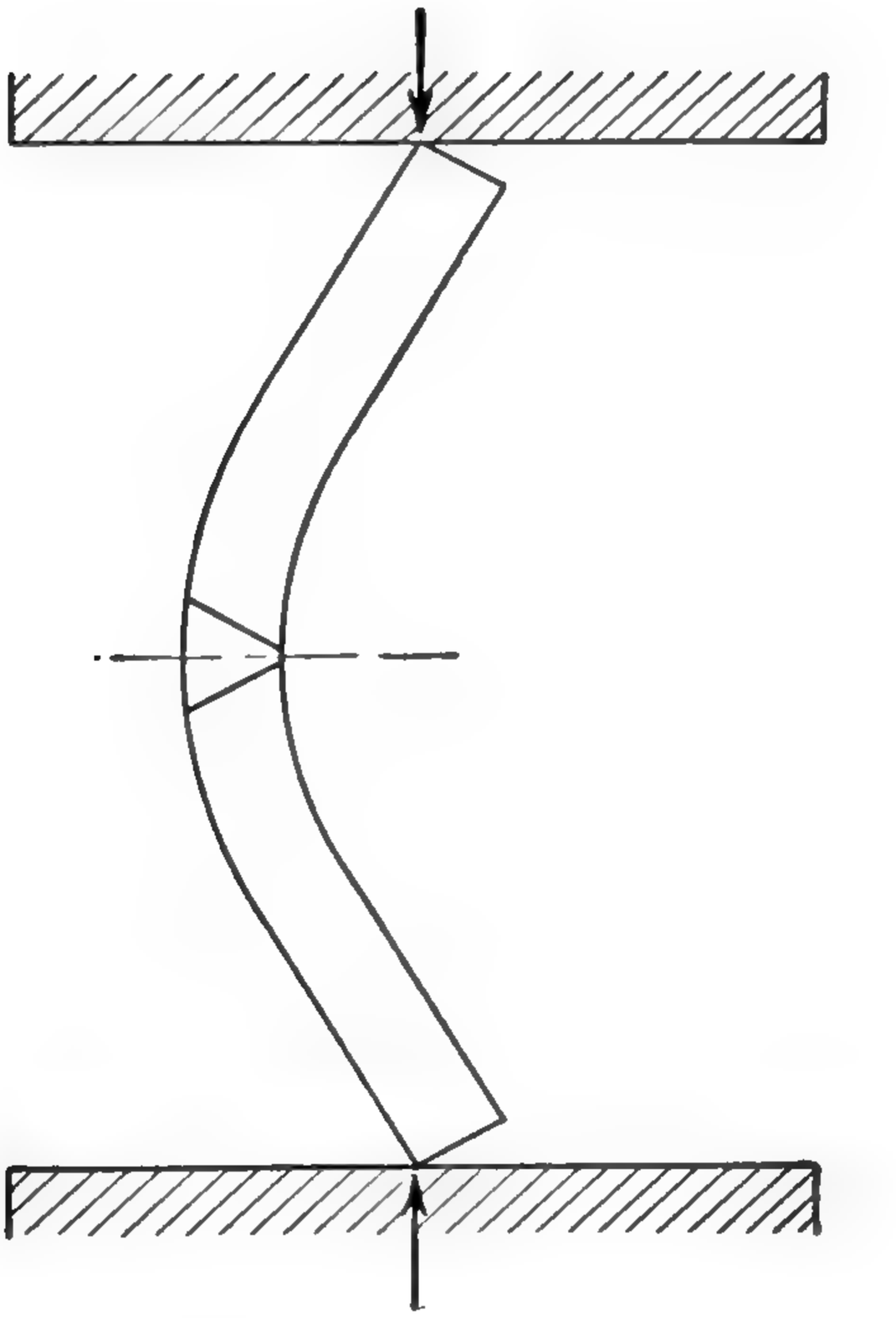


Fig. 19—Final Bend for Free-Bend Specimens

the specimen away from the gage lines through an angle of from 30 to 45° by blows of a hammer. The other end of the specimen shall be bent in the same way. In order that the final bend shall be centered on the weld, the initial bends shall be symmetrical with respect to the weld, and both ends shall be bent through the same angle. In cases of specimens having a thickness of $^1/_2$-in. or less, the initial bend may also be started at the weld by placing the specimen in the guided-bend test jig shown in Fig. 11.

Final Bend: Compressive forces shall be applied to the ends of the specimen, continuously decreasing the distance between the ends, substantially in accordance with Fig. 19. When either a crack or a depression exceeding a specified size in any direction appears on the convex face of the specimen, the load shall immediately be removed. If no crack appears, the specimen shall be bent double. Cracks occurring on the corners of the specimen during testing shall not be considered unless they exceed a similarly specified size.

NOTE: Any convenient means, such as a vise or a testing machine may be used for the final bend. The use of a device complying with Fig. 20 is recommended. It prevents the ends of the specimen from slipping as it is bent. Life and property may be endangered if the specimen slips.

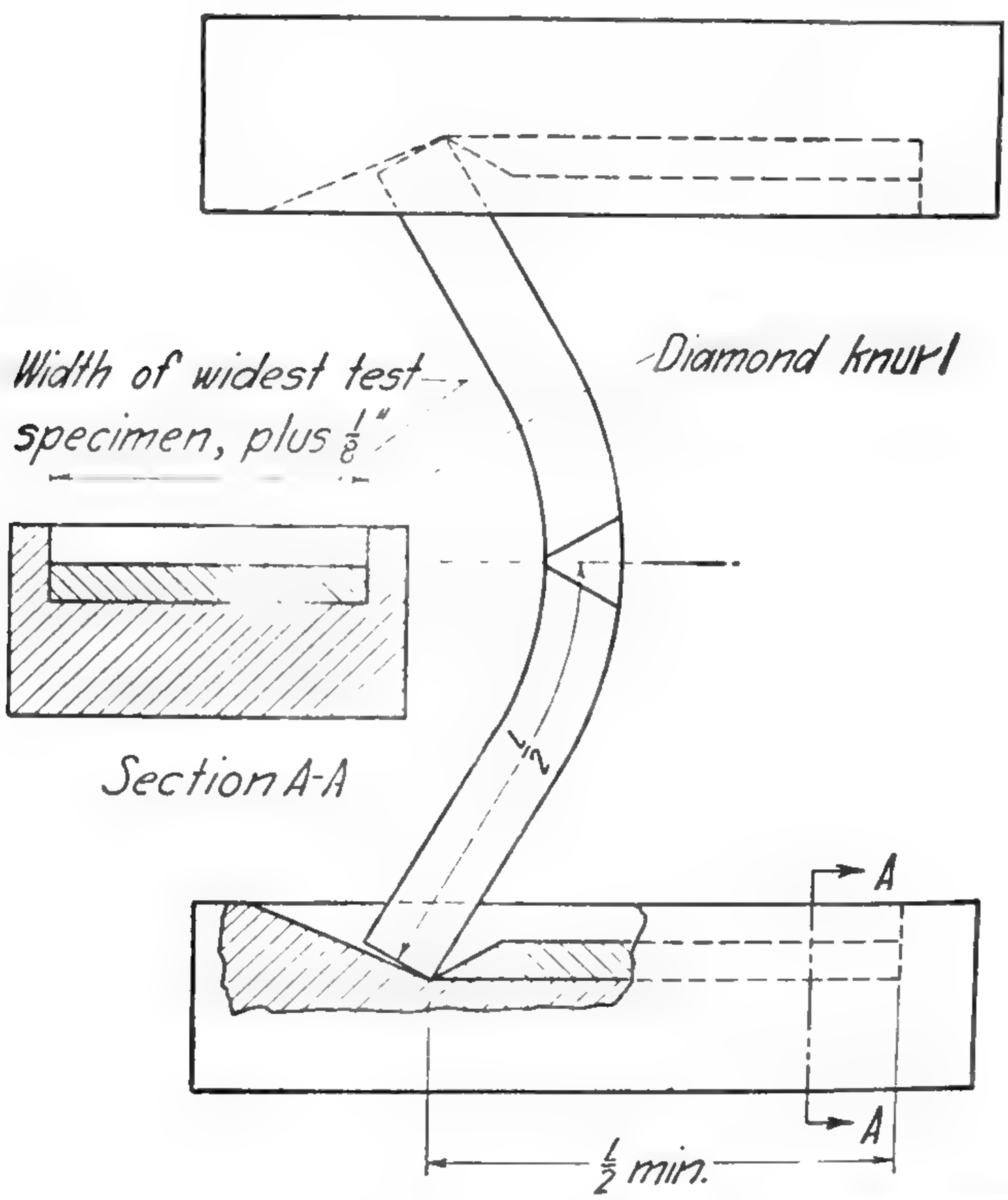


Fig. 20—Recommended Device for Final Bending of Free-Bend Specimens

3. *Results.*—The elongation shall be determined by measuring the minimum distance between the gage lines, along the convex surface of the weld, to the nearest 0.01 inch and subtracting the initial gage length. The per cent *elongation* shall be obtained by dividing the elongation by the initial gage length and multiplying by 100.

NOTE: A flexible steel scale graduated in hundredths of an inch and a magnifying glass may conveniently be used when determining the elongation.

VIII. Fillet-Welded Joints

A. Soundness: Fillet-Weld-Break Test

1. *Specimen.*—The fillet-weld-break specimen, *K*, shall comply with the requirements of Fig. 21.

2. *Procedure.*—A force, *A*, shall be applied to the specimen substantially in accordance with Fig. 22, until rupture of the specimen occurs. The force may be applied by any convenient means.

NOTE: A press, a testing machine or blows of a hammer may be used.

3. *Results.*—The surfaces of the fracture shall be examined for soundness. (See Sec. III and Note Sec. VI, *B* 3).

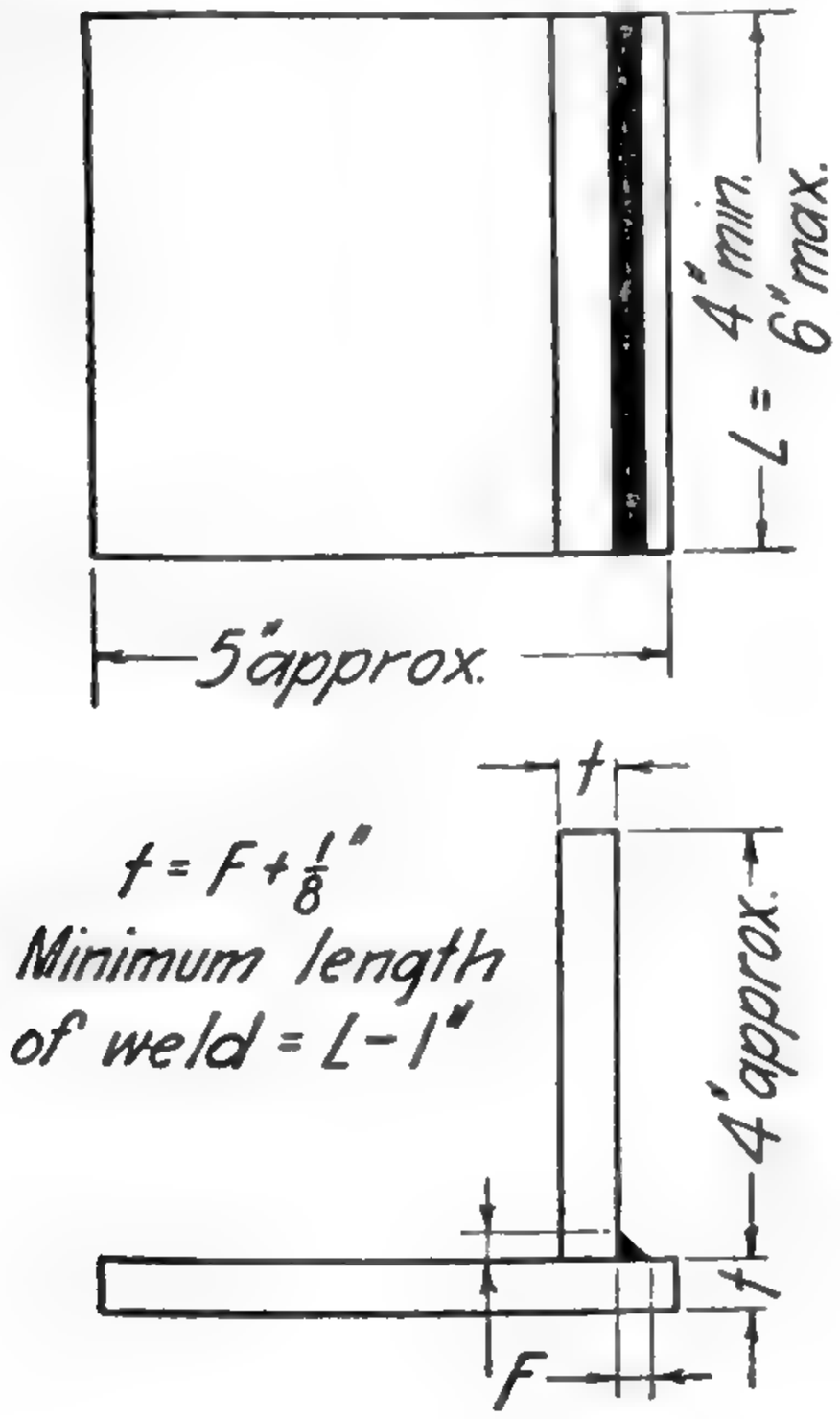


Fig. 21—Fillet-Weld-Break Specimen *K*

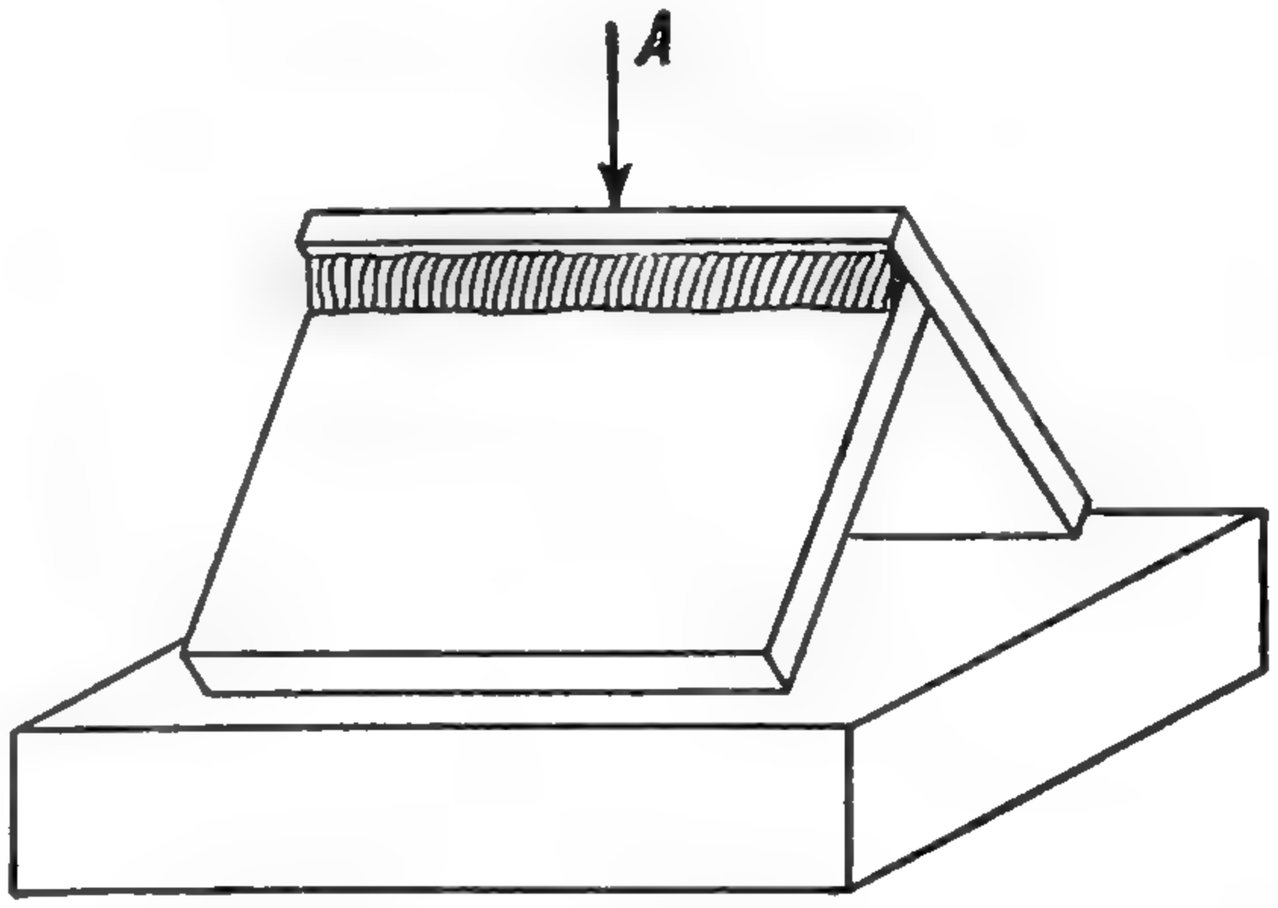


Fig. 22—Method of Rupturing Fillet-Weld-Break Specimen *K*

B. Shearing Strength: Transverse Welds

1. *Specimens.—Type A:* The transverse fillet-weld specimen, *L*-1, shall comply with the requirements given in Fig. 23. (For alternative method of preparing this specimen, see note under paragraph *C* 1.)

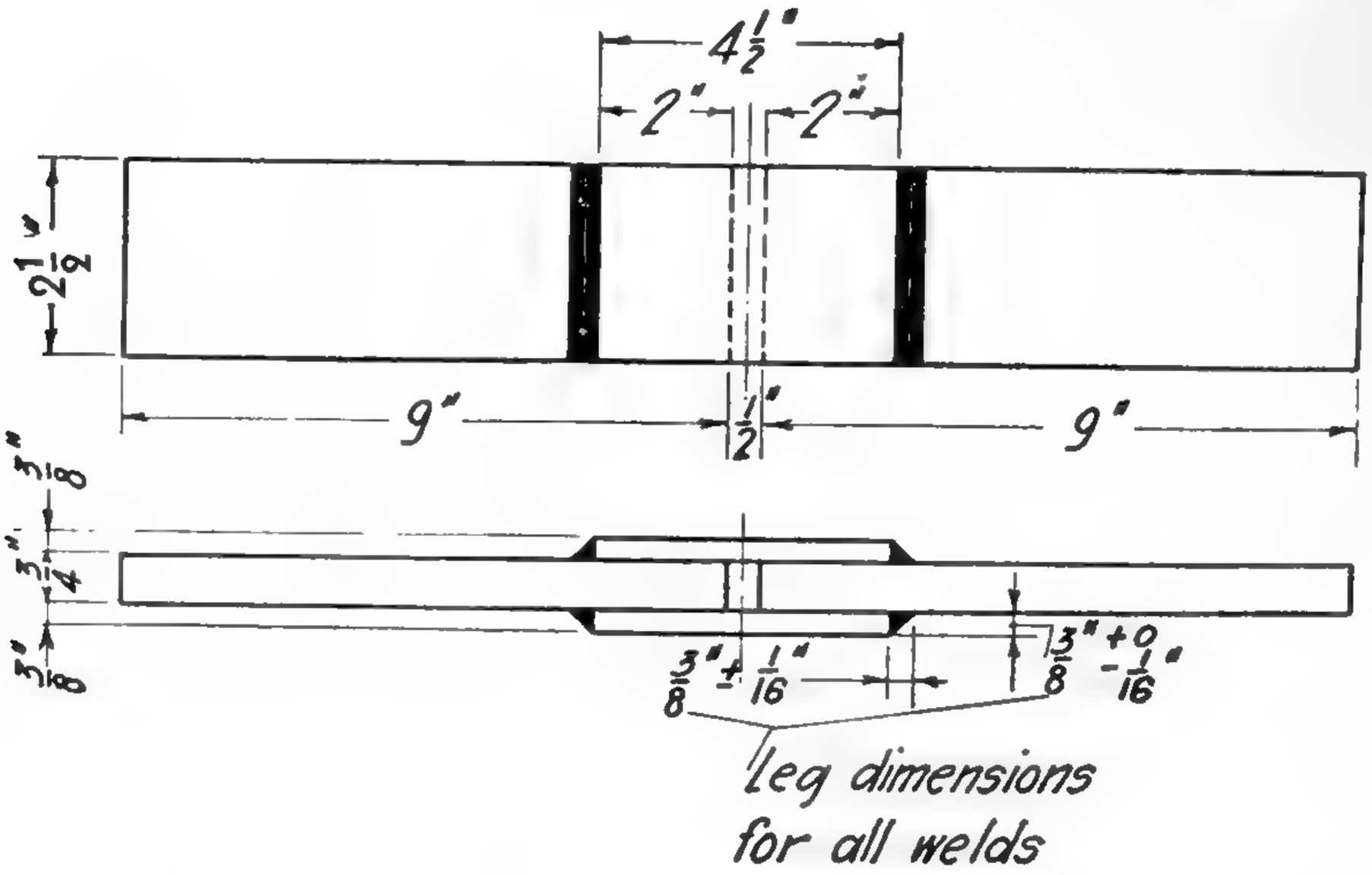


Fig. 23—Transverse Fillet-Weld Shearing Specimen *L*-1

Type B: The transverse fillet-weld specimen, *L*-2, shall comply with the requirements of Fig. 24. (For alternative method of preparing this specimen, see note under paragraph *C* 1.)

NOTE: These two types of specimen are currently used for shear tests of fillet welds; type *A*, where comparative rather than absolute value of strength per linear inch of fillet weld is sufficient, and where because of cost or of time limitations it is desired to avoid machining of specimens, and type *B*, where more nearly exact values are desired.

2. *Procedure.*—The width of the specimen shall be measured in inches. The specimen shall be ruptured under tensile load, and the maximum load in pounds shall be determined.

3. *Results.*—The shearing strength of the welds in pounds per linear inch shall be obtained by dividing the maximum force by twice the width of the specimen.

The shearing strength of the welds in pounds per square inch shall be obtained by dividing the shearing strength in pounds per linear inch by the average throat dimension of the welds in inches.

C. Shearing Strength: Longitudinal Welds

1. *Specimen.*—The longitudinal fillet-weld specimen, *M*, after welding shall comply with the requirements of Fig. 25 and after machining shall comply with the requirements of Fig. 26.

NOTE: For preparing specimens *L*-1, *L*-2, and *M* the following alternative method shall be permissible: Instead of depositing the

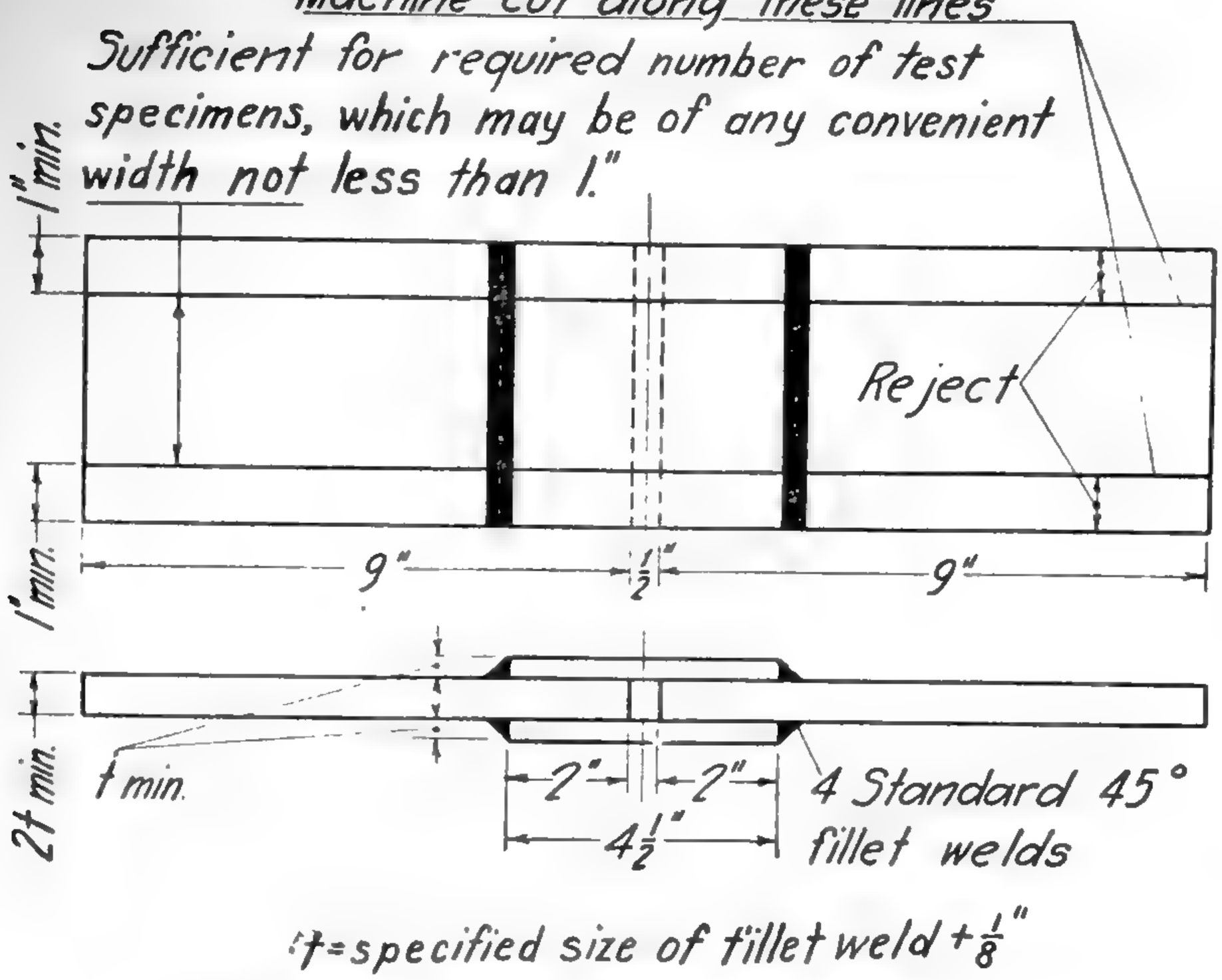
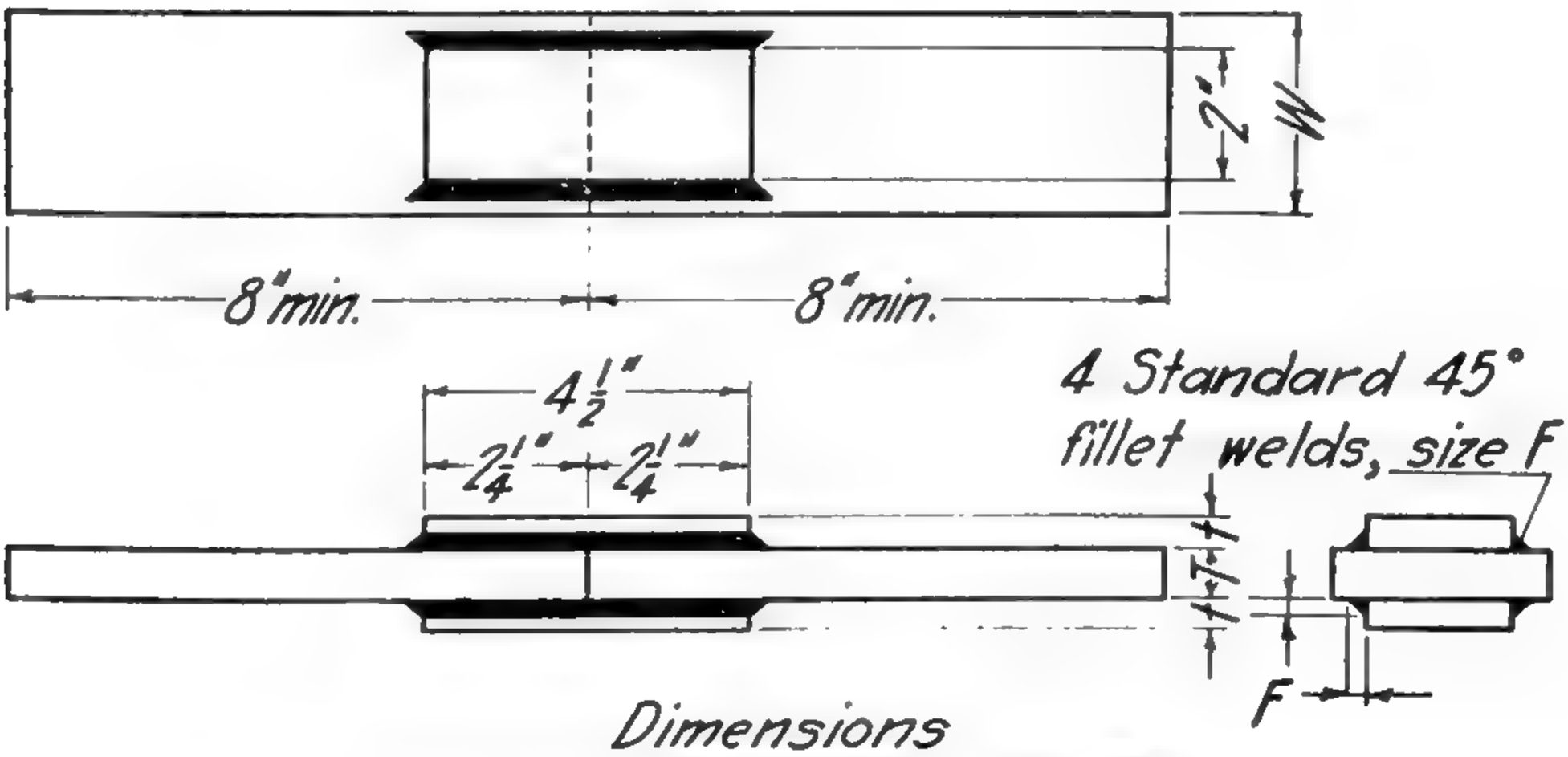


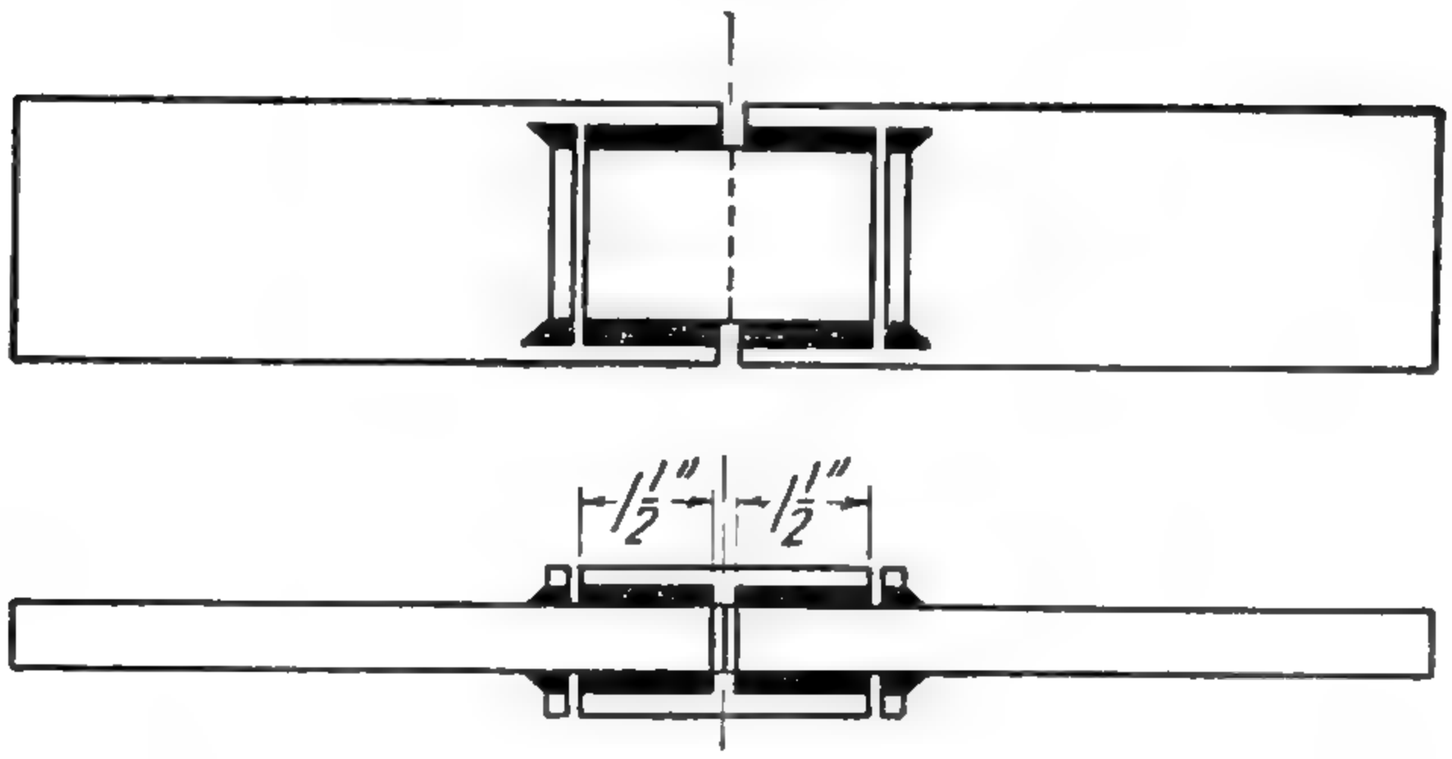
Fig. 24—Transverse Fillet-Weld Shearing Specimen *L*-2



Dimensions

Size of weld F, in.	⅛	¼	⅜	½
Thickness t, in., min.	⅜	½	¾	1
Thickness T, in., min.	⅜	¾	1	1¼
Width W, in.	3	3	3	3½

Fig. 25—Longitudinal Fillet-Weld Shearing Specimen *M* After Welding



Note-for other dimensions see fig. 25

Fig. 26—Longitudinal Fillet-Weld Shearing Specimen *M* After Machining

fillet welds against a single center plate (center plate indicated by dimension "T" in Fig. 25), the welds may be deposited against plates of thickness $^1/_2$ T, where T is the thickness of the center plate, and the specimen prepared in two halves as shown in Fig. 27 (*a*). The two halves of the specimen shall then be placed back-to-back and united by means of an edge joint (made with a bead weld or a $^5/_{32}$-in. 90-degree single-V groove weld, deposited by the metal arc process), as shown in Fig. 27 (*b*).

2. *Procedure.*—The length of each weld shall be measured in inches. The specimen shall be ruptured under tensile load, and the maximum force in pounds shall be determined.

3. *Results.*—The *shearing strength* of the welds in pounds per linear inch shall be obtained by dividing the maximum force by the sum of the lengths of the welds which ruptured.

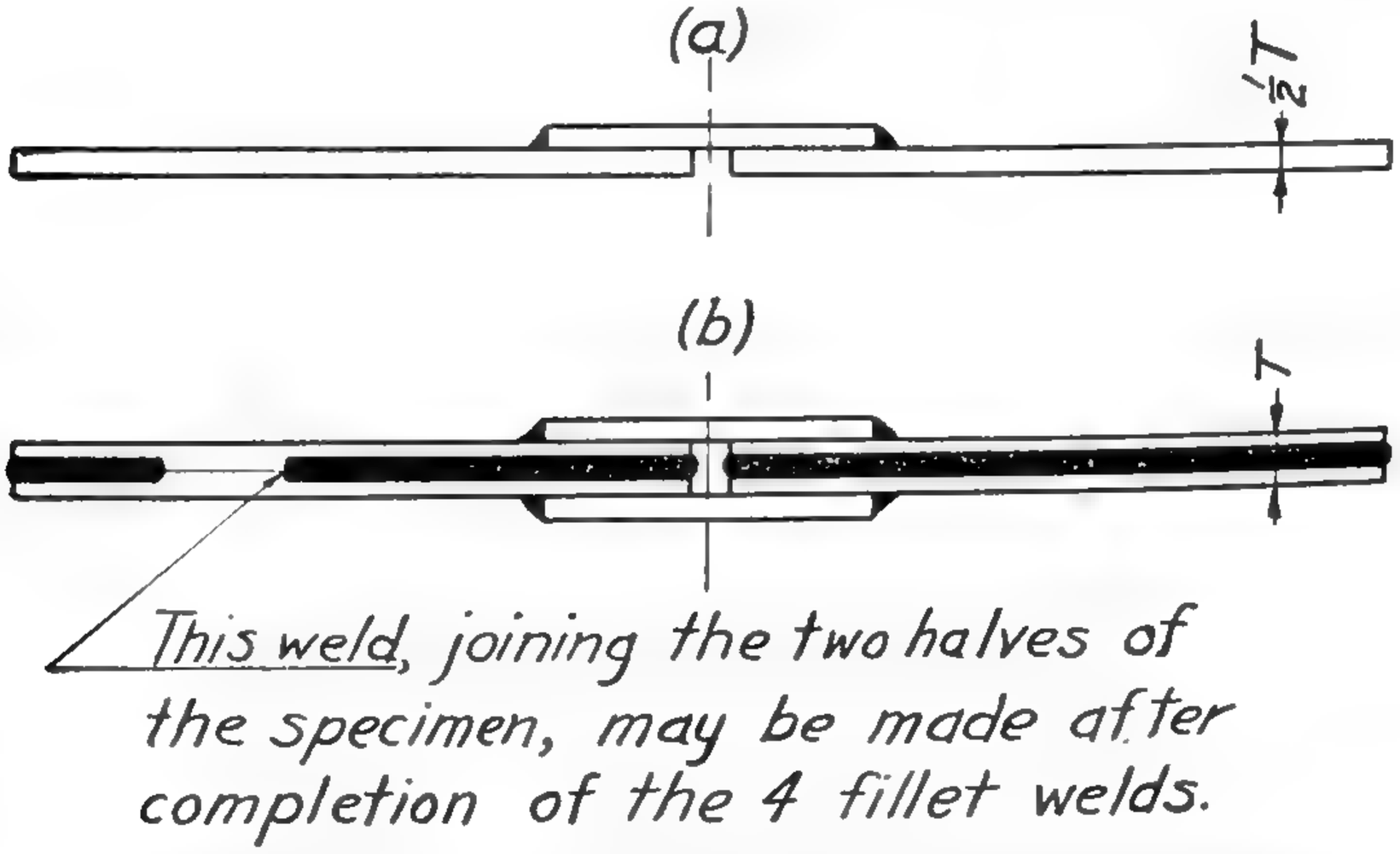


Fig. 27—Alternate Method of Preparing Fillet Weld Shearing Specimens (Specimen illustrated is transverse shearing specimen. For specific details and dimensions see Figs. 23, 24 and 25.)

Approved as a Tentative Standard September 13, 1945

Weldability: Tee-Bend Test[1]

1. Preparation of Specimen Assembly

(*a*) *Dimensions of Specimen Assembly.*—The specimen assembly for the tee-bend test shall conform to the dimensions given in Fig. 1.

(*b*) *Condition of Specimen Assembly.*—The plates of the specimen assembly shall be of the material under investigation, and shall be in the as-rolled condition unless otherwise specified. They shall be prepared so that the welding will be transverse to the direction of rolling. Loose scale and other foreign material shall be removed by wire brushing from the surfaces of the assemblies prior to welding.

(*c*) *Temperature of Assembly Prior to Welding.*—The specimen assembly shall be at a temperature of 75° F. ± 10° F. when welding is started.

(*d*) *Welding Procedure.*—The welds shall be deposited in the flat position to obtain a single-layer continuous fillet. The assembly shall return to the original temperature by cooling in still air before deposition of the fillet weld on the opposite side of the vertical member.

The following standard conditions shall be used for the deposition of the fillet welds:

Plate thickness	$^1/_2$ in.
Electrode classification	E6010[2]
Electrode size	$^5/_{32}$ in.
Arc voltage	26 to 28 volts
Amperage	130 to 135 amp.
Fillet size	See note below

NOTE: The fillet welds shall be deposited as follows: Increments $2^{11}/_{16}$ inches long of complete fillet shall be deposited with $9^1/_4$ to $9^3/_4$ inches of electrode. As many successive increments of this length shall be deposited as is necessary to weld the fillet along the entire length of test plate. A period of exactly 45 seconds should elapse between the deposition of increments to permit change of electrodes. This method of deposition controls the volume of the weld metal and permits the deposition of similar fillets on all specimens.

The welding of the second fillet shall be in the opposite direction from that of the first fillet. The result shall be welds free from undercutting and surface porosity and approaching as nearly as possible a 45-degree right triangle.

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[1] This method of test is intended to measure the angle of bend and type of fracture of a standardized welded specimen of a given steel as indications of the comparative welding quality of that steel. The test indicates the combined effects of variables such as chemical composition, previous processing and defects present in the particular sample.

[2] This classification number refers to the A.W.S.-A.S.T.M. Tentative Specifications for Iron and Steel Arc-Welding Electrodes (ASTM Serial Designation A233).

2. *Preparation of Specimens*

(*a*) *Removal from Assembly.*—The specimens (four for bend tests and one for hardness tests and microscopic examination, if desired) shall be removed from the assembly as shown in Fig. 1, by sawing or milling. The removal of specimens by flame cutting shall not be permitted.

(*b*) *Tee-Bend Specimens.*—The surfaces of the specimens shall not be filed, ground or machined in any manner. The tension edges shall be broken slightly with a file.

3. *Testing of Bend Specimens*

(*a*) *Specimens.*—Ordinarily two bend specimens from one assembly are tested at a given temperature. The extra specimens may be used for replacing rejected specimens or for testing at elevated or subnormal temperatures. If all specimens from one assembly are rejected a new assembly shall be fabricated under the same conditions as the original assembly.

(*b*) *Bending Apparatus.*—The essential features of the bending jig shall be as shown in Fig. 2.[3]

NOTE: Testing is normally done at room temperature but if information concerning low-temperature bending properties is desired, the jig and specimen must be placed in a tank and completely covered with a cooling liquid during the entire period of test.

(*c*) *Procedure.*—The vertical member of the specimen shall be secured in the slot of the cross-head of the bending apparatus, and the horizontal member supported on the rolls as shown in Fig. 2. Pressure shall be applied through the plunger attached to the movable head of a testing machine which may be of a vertical screw or hydraulic type, and with a beam, dial or other suitable means for indicating the load. The downward feed of the plunger shall be continued until the angle of bending is 120 degrees or until the specimen has entirely fractured.

4. *Results of Tee-Bend Tests*

(*a*) *The Maximum Load*, indicated by a drop of the beam or by the highest load indicated on the dial, shall be recorded.

(*b*) *The Bending Angle* shall be measured[4] and recorded at the point of failure or drop of the beam indicating maximum load has been reached.

NOTE: This angle is the supplement of the included angle through which the base plate of the assembly has been bent or the sum of angles *A* and *B*, Fig. 3.

(*c*) *Fractures* shall be classified as follows (see Fig. 4):

Type 0 fracture: The specimen bends to 120° without fracture or tear of any kind.

Type 1 fracture: A crack which starts at the toe of the fillet and follows the bend zone or the heat-affected zone under the weld but does not turn into the plate metal.

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[3] Detailed dimensions of the bending jig are shown in Fig. 5. For those interested in 1/4- and 3/4-inch specimens, dimensions of jigs for these thicknesses are also included.

[4] The bend angle may be measured either by the relative movement of the jig member or by removing the specimen from the jig and measuring the angle. Both methods have been used. The former, however, is preferred, because of its simplicity. A scale on the piston (Fig. 5*a*) is used for the purpose of measuring the deflection from which the angle may be determined. The angle measured after the specimen is removed from the jig will be slightly lower than that measured by deflection due to a slight spring back after removal of the load. Whichever method is used should be consistently used and noted.

Type 2 fracture: A slowly progressing crack which starts at the toe of the fillet and extends either directly into the plate material or follows the bond zone or heat-affected zone for a short distance and then turns into the plate metal.

Type 3 fracture: A sudden or sharp crack which generally starts at the toe of the fillet and extends directly or perpendicularly in the plate metal.

NOTE: Specimens which either before or after testing exhibit laminations, splits, seams or similar plate defects shall cause rejection of the specimens.

5. *Recording of Results*

The results of the test shall be recorded on a suitable permanent form.
NOTE: The following form for reporting the results is recommended:

RECORD OF TEE-BEND TEST

Material and Welding Procedure										
1. Type of Steel										
2. Chemical Composition	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V
3. Deoxidation Practice			Killed		Semi-Killed				Rimmed	
4. Grain Size (McQuaid-Ehn)										
5. Heat Treatment										
6. Electrode Brand										
7. Original Plate Temperature										
8. Testing Temperature										

Bend Test Results	Spec. #1	Spec. #2
9. Maximum Load		
10. Angle of Bending at Maximum Load		
11. Load at Initial Fracture		
12. Angle of Bending at Initial Fracture		
13. Type of Fracture		
14. Hardness of Heat-Affected Zone (Max.)*		
15. Hardness of Unaffected Plate Metal (Avg.)*		
16. Remarks:		

* Hardness curves are not specified in this test procedure. However, some investigators prefer to include hardness surveys and these items are listed here for their convenience.

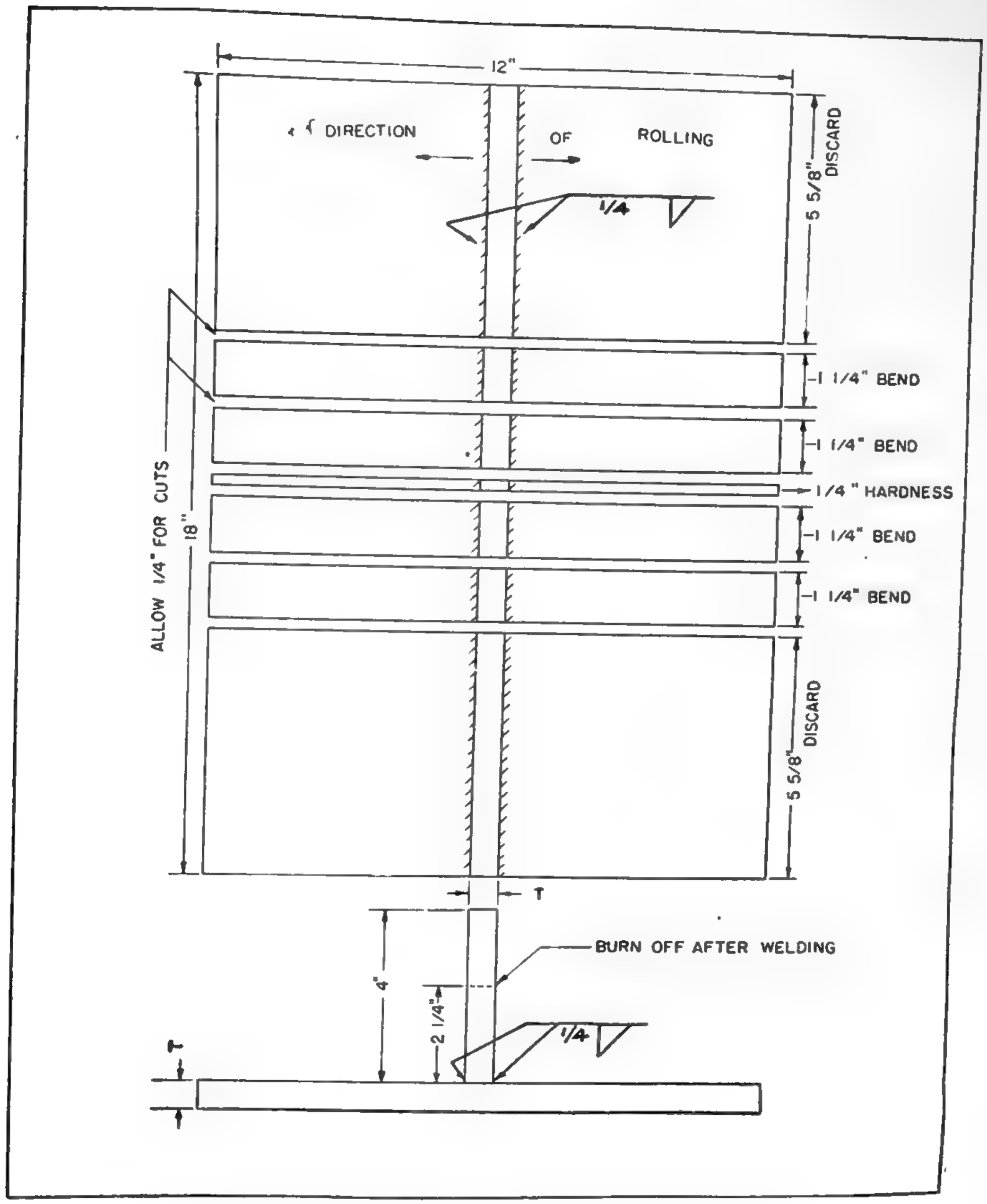


Fig. 1—Location of Test Specimens (see Paragraph 1)

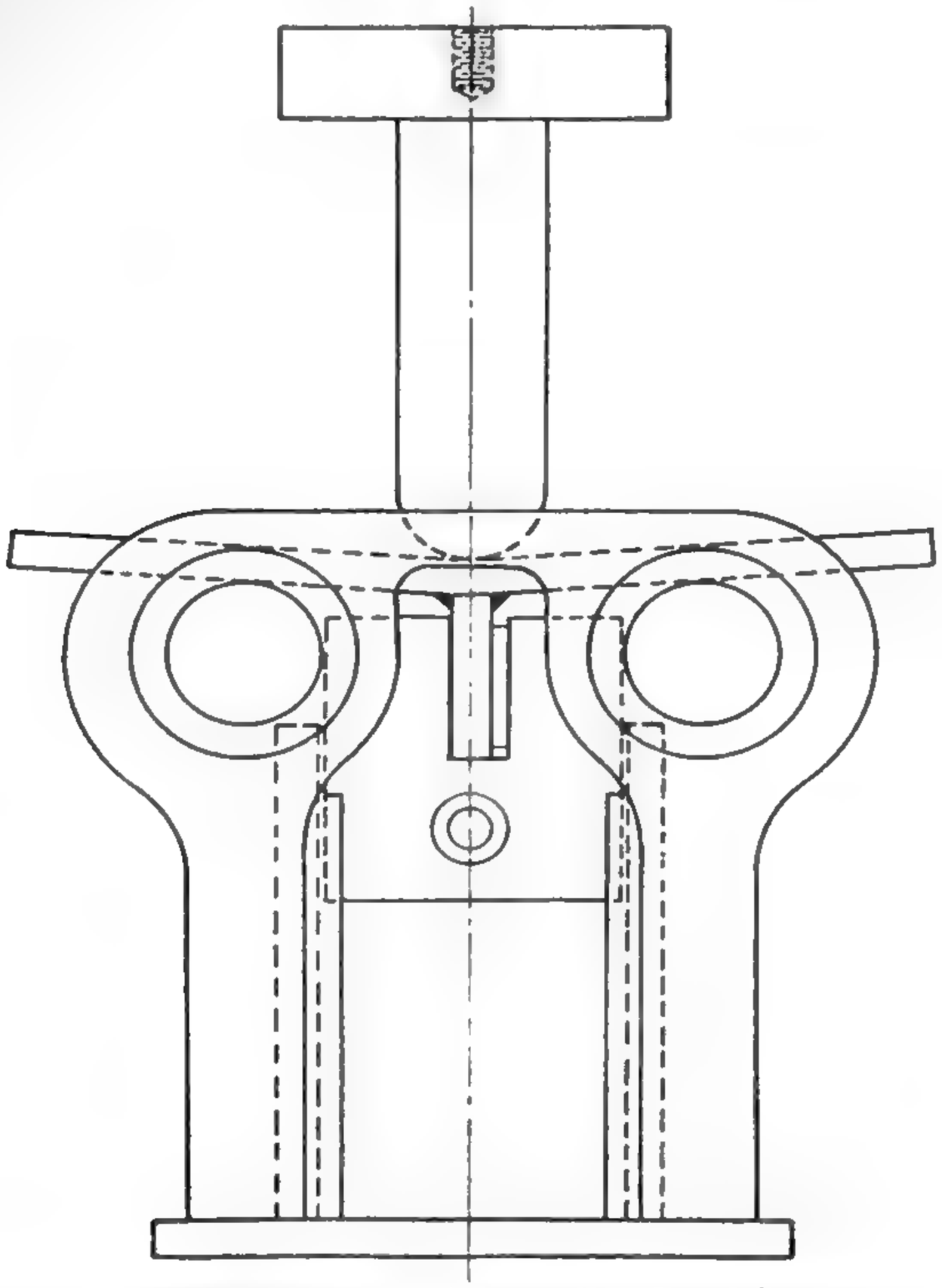


Fig. 2—Bending Jig for 1/2-Inch Tee-Bend Specimens

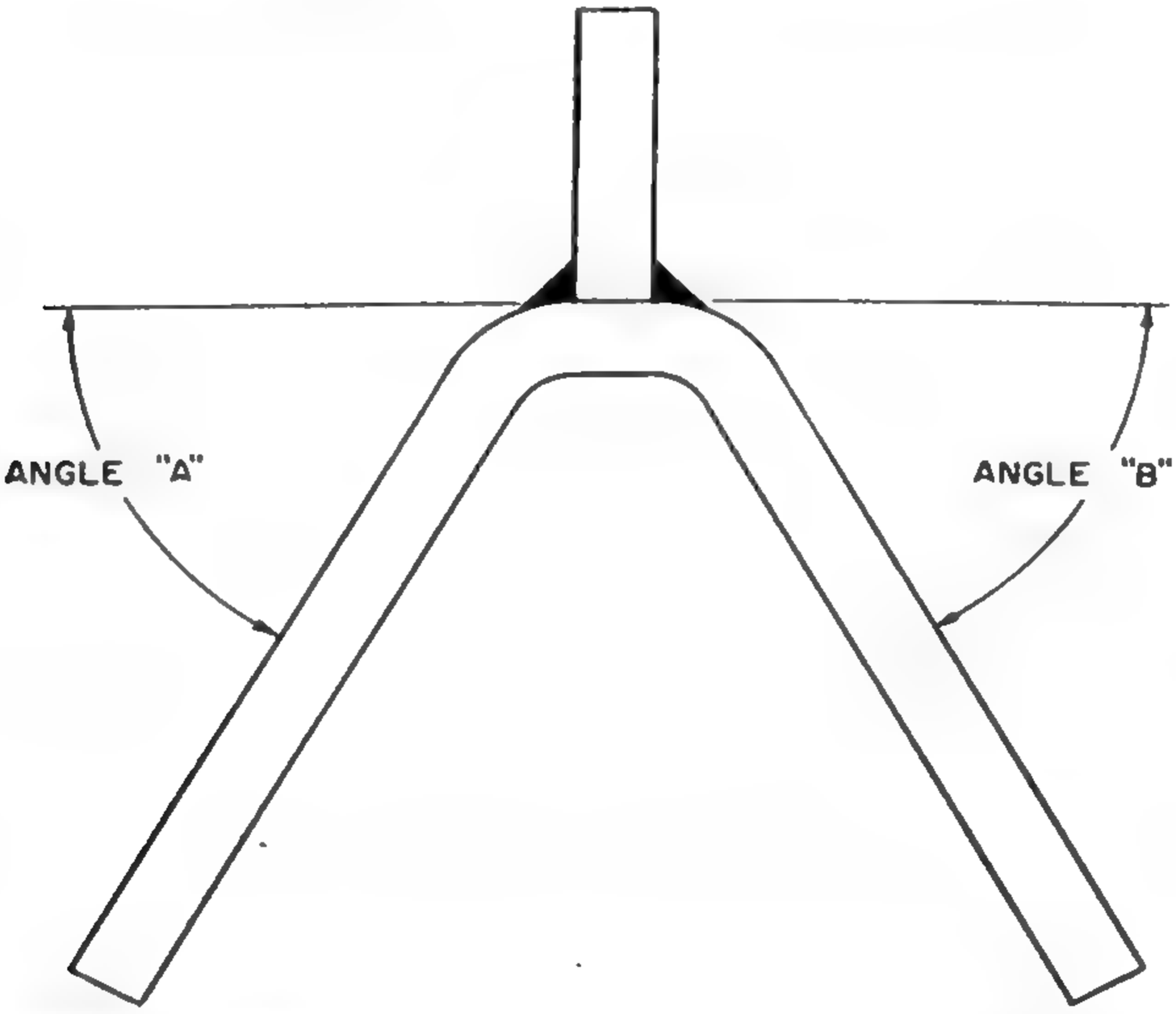
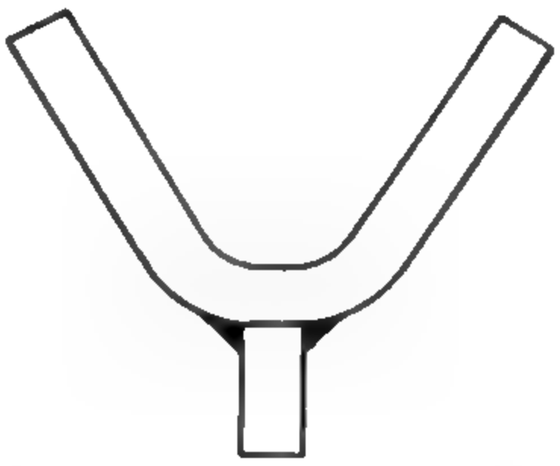
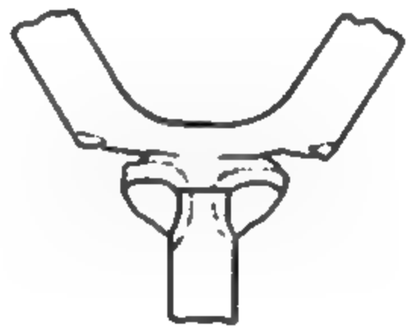


Fig. 3—Method of Measuring Angle of Tee-Bend Specimens (see Paragraph 4b)



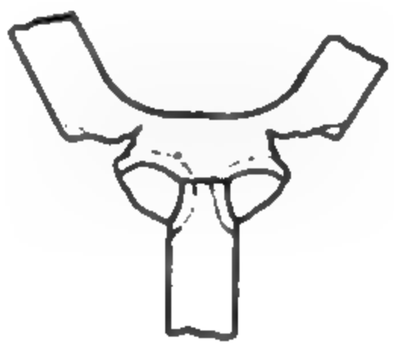
TYPE "0"

NO FAILURE



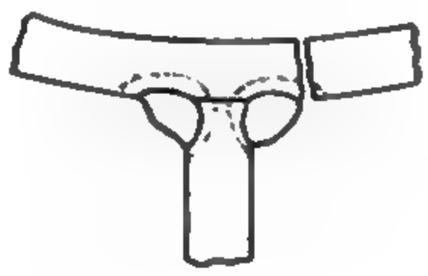
TYPE "1" FRACTURE

A CRACK WHICH STARTS AT THE TOE OF THE FILLET AND FOLLOWS THE BOND ZONE OR THE HEAT AFFECTED ZONE UNDER THE WELD BUT DOES NOT TURN INTO THE PLATE METAL.



TYPE "2" FRACTURE

A SLOWLY PROGRESSING CRACK WHICH STARTS AT THE TOE OF THE FILLET AND EXTENDS EITHER DIRECTLY INTO THE PLATE MATERIAL OR FOLLOWS THE BOND ZONE OR HEAT AFFECTED ZONE FOR A SHORT DISTANCE AND THEN TURNS INTO THE PLATE METAL.



TYPE "3" FRACTURE

A SUDDEN OR SHARP CRACK WHICH GENERALLY STARTS AT THE TOE OF THE FILLET AND EXTENDS DIRECTLY OR PERPENDICULAR IN THE PLATE METAL.

Fig. 4—Types of Fracture (see Paragraph 4c)

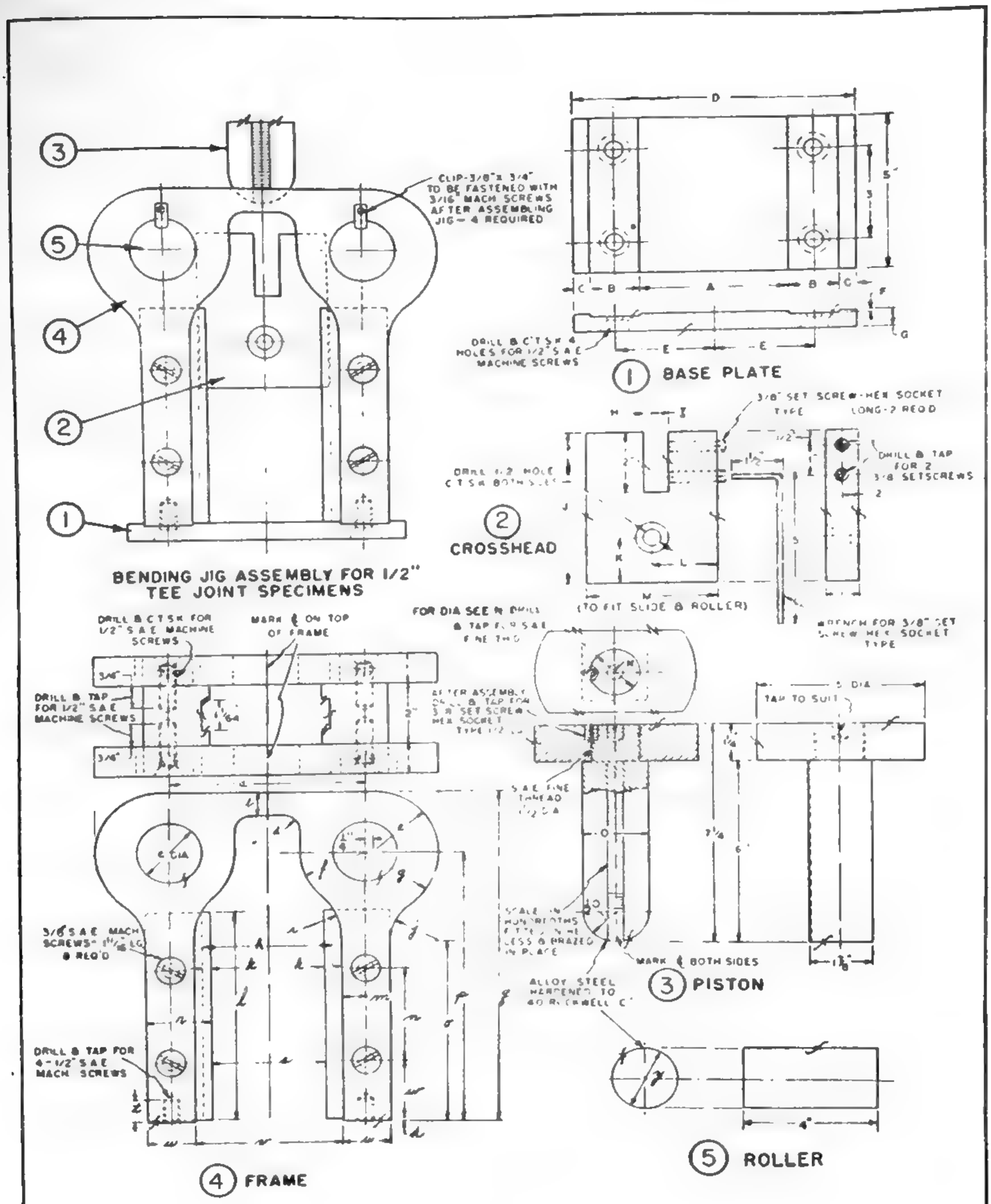


Fig. 5(*a*)—Bending Jig for 1/4, 1/2 and 3/4-Inch Specimens

TABLE FOR BASEPLATE REF. 1			
DIMENSION	1/4" TEE	1/2" TEE	3/4" TEE
A	2 - 1/4"	4 - 1/2"	6 - 3/4"
B	3/4"	1 - 1/2"	2 - 1/4"
C	5/8"	1/2"	1"
D	5"	8 - 1/2"	13 - 1/4"
E	1 - 1/2"	3"	4 - 1/2"
F	1/16"	1/16"	1/8"
G	1/2"	9/16"	3/4"
TABLE FOR CROSSHEAD REF. 2			
H	1/8"	1/4"	3/8"
I	3/8"	1/2"	5/8"
J	4"	5"	6"
K	1"	1 - 1/2"	2"
L	1/2 M	1/2 M	1/2 M
M	1 - 63/64"	3 - 63/64"	5 - 63/64"
TABLE FOR PISTON REF. 3			
N	3/4"	1 - 1/2"	3 - 1/2"
O	1"	2"	5"
TABLE FOR FRAME REF. 4			
a	3"	6"	9"
b	1/2"	3/4"	1"
c	1"	2"	3"
d	1/4"	1/2"	1/2"
e	7/8"	2"	2 - 3/4"
f	3/4"	2"	2" - 3/4"
g	1 - 1/8"	2 - 1/4"	3"
h	2"	4"	6"
i	3/4"	1 - 3/4"	2"
j	3/4"	1 - 1/2"	2"
k	1/8"	1/4"	1/4"
l	4 - 15/16"	7 - 13/16"	6 - 7/8"
m	3/8"	3/4"	1 - 1/8"
n	2"	3"	3"
o	4 - 1/16"	6"	5 - 1/4"
p	5 - 9/16"	9"	9 - 1/8"
q	6 - 7/16"	11"	11 - 7/8"
r	1"	2"	2 - 7/8"
s	1 - 3/4"	3 - 1/2"	5 - 1/2"
t	3/4"	1"	1 - 1/4"
u	3/4"	1 - 1/2"	2 - 1/4"
v	2 - 1/4"	4 - 1/2"	6 - 3/4"
w	1 - 1/2"	2"	1 - 11/16"
x	1/16"	1/16"	1/8"
TABLE FOR ROLLER REF. 5			
y	1"	2"	3"

Fig. 5(*b*)—Table of Dimensions of Bending Jig for 1/4, /2 and 3/4-Inch Specimens

NOTE: 1/4-inch and 3/4-inch specimens are not standard. Dimensions of jigs for these thicknesses included for information only.

CHAPTER 60

STANDARD QUALIFICATION PROCEDURE*

Section I

Manual Arc and Gas Welding of Ferrous Materials

FOREWORD

It is recognized that the quality of arc- and gas-welded joints will be determined by the specific welding procedure used and by the ability of the welding operator to apply that procedure. Predictable results as to the physical properties and soundness of such joints can be secured only by adherence to a procedure of welding that has been thoroughly investigated. It cannot be expected that good results will be obtained, even by careful and painstaking workmen, if poor material, inadequate or worn out equipment are used, or if fundamentally improper methods are pursued. Nor can the purpose of welding be obtained by the mere adoption of a carefully outlined procedure of welding, if the welding operators have not been given a certain degree of training and are not properly supervised to be certain that all essential details of the specific procedure for welding are followed.

In arc and gas welding, the physical properties of the weld metal, such as tensile strength and ductility, will be determined by the particular procedure of welding that is used. The reliability of the welded joint will be determined by the degree to which that weld metal is kept free of foreign materials, such as slag, and by the degree to which it is fused to the base material. Under a fixed procedure of welding these two latter factors are the only ones over which the welding operator has control. It is considered unnecessary, therefore, to test welds of every operator for tensile strength and ductility. It is the belief of the Committee that the first step in welding must be the adoption of a procedure of welding in which all essential variables are fixed within definite limits. The procedure for welding should then be investigated to determine whether it will produce welds with the desired physical properties. The tests required for a welding operator are included in the investigation of a welding procedure because there have been many instances wherein failure to obtain results has been attributed to the inability of the operator when the difficulty lay in the fundamentals of the procedure. Having established that a given procedure is satisfactory, comparatively simple tests, intended primarily to determine the ability of an individual to make a sound weld, may then be used for the qualification of welding operators.

In Part I there is given the method to be pursued in investigating and qualifying a welding procedure, while Part II outlines the method of qualifying welding operators.

There are several variables involved in any procedure of welding, and if predictable results are to be obtained, certain limitations must be placed

* Prepared by the AWS Committee on Standard Qualification Procedure.

upon those variables before the procedure for welding is tested. Having fixed upon these limitations, it is necessary that some tolerance or degree of departure from a given limitation of a variable, as stated in a procedure specification, be recognized as permissible without requiring that a retest of the procedure be made. Such departures from a fixed procedure of welding as might affect the predictable results to be obtained, may be referred to as essential changes. The tests which must be made to determine the effect that a given essential change will have upon the predictable results will depend upon the nature of that change. In some cases a test of the procedure for welding, embodying the change, will be necessary, in other cases a test of the welding operator only will be sufficient, and in still other cases a test of both the new procedure and the individual operators will be required.

A tabulation of the variables and of those changes in variables which are considered to be essential changes, together with the type of investigation necessary—whether of procedure, operator or both—is given in Article 101.

The Committee has given much thought to the need for simplification of the test of a welding operator, and the type of tests outlined herein are designed to ascertain that the operator has a sufficient knowledge of and the skill to apply a procedure of welding under average conditions. For this purpose, a special shape of welding groove, intended to be used only for operator test specimens, has been adopted.

The Committee has also been seeking and now presents a type of operator test specimen for fillet welded joints that may be readily tested in a guided bend test jig, thus providing a test that is not only inexpensive and simple to make, but also one that avoids question of judgment as to the results obtained.

It is the conviction of the Committee that there are so many essential factors involved in the successful application of arc and gas welding, embracing such items as quality of filler metal, adaptability of the welding procedure and equipment, facilities provided for preparing the work, etc., that the manufacturer or contractor alone should be expected to be responsible for the integrity of the finished weld. It should be borne in mind that it is the manufacturer or contractor who is financially responsible for the quality of the welding performed and that in the case of failure thereof the welding operator assumes no share of the financial burden. In these rules, therefore, the entire responsibility for quality of the welding performed will be assumed to lie with the manufacturer or contractor.

The Committee will be pleased to provide any interpretations that may assist in the application of this standard.

GENERAL

These rules are intended to apply only to the manual application of the arc- and gas-welding processes, and to those ferrous metals which in their unwelded condition will meet the requirements of the guided bend test prescribed herein.

Each manufacturer or contractor shall be responsible for the quality of the welding done by his organization and shall conduct tests not only of the welding procedure to determine its suitability to ensure welds which will

meet the required tests, but also of the welding operators to determine their ability to make sound welds under standardized test conditions.

It is assumed that the manufacturer or contractor has an organization familiar with the various welding codes and capable of designing, engineering and supervising welded construction.

Rules for the qualification of a welding procedure are given in Part I. Rules for qualifying operators follow in Part II.

PART I—PROCEDURE QUALIFICATION

101. Limitation of Variables

(*a*) The procedure of welding to be followed in construction shall be established and recorded by the manufacturer or contractor as a Procedure Specification, and in the investigation to qualify this procedure, the Procedure Specification shall be followed. Recommended forms for the Procedure Specification are given in the Appendix. It is not necessary that these exact forms be used, but the information contained therein should be set forth in any alternate form which is adopted.

(*b*) If any changes are made in a procedure, the Procedure Specification shall be revised or amended to show these changes.

The changes set forth in the following schedule shall be considered essential changes and shall require requalification of the procedure or operator or both. Any change marked "P" or "PO" shall require requalification of the procedure; any change marked "PO" or "O" shall require requalification of the operator.

P	1	A change in the specification of base metal to be welded from one "P" Number to another "P" Number. (See Table 5.)*
PO	2	A change in the specification of base metal to be welded from one "O" Number to another "O" Number. (See Table 5.)
PO	3	A change in filler metal from one American Welding Society Specification** to another Specification.
P	4	A change in filler metal from one American Welding Society Classification Number† to another American Welding Society Classification Number.
O	5	A change in filler metal from a bare or lightly coated electrode to a covered electrode, or vice versa, within any given American Welding Society specification for arc welding electrodes.‡

* When any "P" group in Table 5 contains materials having specified minimum tensile strengths higher than the tensile strength obtained in the actual procedure qualification tension test, it may be desirable for governing codes to require procedure qualification using these higher tensile materials before they can be welded in actual construction.

** See American Welding Society filler metal specifications.

† For example: A change from an E6010 to an E6012 or E7010 electrode (Tentative Specifications for Iron and Steel Arc Welding Electrodes); or a change from a G60 to a G45 or G65 welding rod (Tentative Specifications for Iron and Steel Gas Welding Rods).

‡ For example: A change from an E6010 to an E4510 electrode requires requalification of the operator; a change from an E6010 to an E6020 or E6030 electrode *does not* require requalification of the operator (Tentative Specifications for Iron and Steel Arc Welding Electrodes).

P	6	An increase in the diameter of the electrode or welding rod used, over that called for in the Procedure Specification.
P	7	A change of more than 15 per cent above or below the specified mean arc voltage and amperage for each size electrode used.
P	8	For a specified welding groove, a change of more than plus or minus 25 per cent in the specified number of passes. If the area of the groove is increased, it is also permissible to increase the number of passes in proportion to the increased area.
PO	9	A change in the position in which welding is done as defined in Articles 104 and 204.
O	10	In the case of vertical welds, a change from the progression specified for any pass from upward to downward or vice versa.
P	11	A decrease in the preheating temperature.
P	12	A change in the heat-treating temperature range or time range.
P	13	A change in the specified range of sizes of gas-welding tips.
P	14	A change of gas-welding flame from neutral to one with an excess of acetylene or vice versa.
O	15	A change from the "backhand" to the "forehand" method of welding. (Gas or carbon arc welding.)
P	16	A decrease in the number of layers used in gas welding.
P	17	A change in the type of welding groove. (Example, change from a V to a U shape.)
P	18	A change in the shape of any one type of welding groove involving: (1) a decrease in the included angle of the welding groove, or a decrease in the width of the groove; or (2) a decrease in the root opening of a welding groove; or (3) an increase in the root face of a welding groove; or (4) the addition or omission of a backing strip.

102. Types of Tests and Purposes

The types of tests outlined below are to determine the tensile strength, ductility and degree of soundness of welded joints made under a given Procedure Specification. The tests used are as follows:

(*a*) *For Groove Welds*

(1) Reduced-Section Tension Test (for Tensile Strength)
(2) Free-Bend Test (for Ductility)
(3) Root-Bend Test (for Soundness)
(4) Face-Bend Test (for Soundness)
(5) Side-Bend Test (for Soundness)

(*b*) *For Fillet Welds*

(1) Longitudinal or Transverse Shear Test (for Shear Strength)
(2) Free-Bend Test (for Ductility)
(3) Fillet-Weld-Soundness Test (for Soundness)

103. Base Material and Its Preparation

The base material and its preparation for welding shall comply with the

Procedure Specification.* For all types of welded joints the length of the weld and the dimensions of the base material shall be such as to provide sufficient material for the test specimens called for hereinafter.

104. Position of Test Welds

All welds that will be encountered in actual construction, except groove welds in pipe, shall be classified as being (1) Flat, (2) Horizontal, (3) Vertical or (4) Overhead, in accordance with the definitions of welding positions given in Fig. 1 (*a*) and 1 (*b*). Groove welds in pipe shall be classified as (1) Horizontal Rolled, (2) Horizontal Fixed or (3) Vertical, in accordance with the definitions of pipe welding positions given in Fig. 1 (*a*). Each procedure shall be tested in the manner stated below for each position for which it is to be qualified.

(*a*) *Groove Welds in Plate*

In making the tests to qualify groove welds in plate, the test plates shall be welded in the following positions:

(*1*) *Flat Position*—The test plates shall be placed in an approximately horizontal plane and the weld metal deposited from the upper side. (Illustrated in Fig. 21 (*a*).)

(*2*) *Horizontal Position*—The test plates shall be placed in an approximately vertical plane with the welding groove approximately horizontal. (Illustrated in Fig. 21 (*b*).)

(*3*) *Vertical Position*—The test plates shall be placed in an approximately vertical plane with the welding groove approximately vertical. (Illustrated in Fig. 21 (*c*).)

(*4*) *Overhead Position*—The test plates shall be placed in an approximately horizontal plane and the weld metal deposited from the under side. (Illustrated in Fig. 21 (*d*).)

(*b*) *Groove Welds in Pipe*

In making the tests to qualify groove welds in pipe, the pipe shall be welded in the following positions:

(*1*) *Horizontal Rolled*—The pipe shall be placed with its axis in an approximately horizontal plane with the welding groove in an approximately vertical plane and the pipe shall be rolled during welding. (Illustrated in Fig. 21 (*a*).)

(*2*) *Horizontal Fixed*—The pipe shall be placed with its axis in an approximately horizontal plane with the welding groove in an approximately vertical plane and the pipe shall not be rolled or turned during welding. (Illustrated in Fig. 21 (*e*).)

(*3*) *Vertical*—The pipe shall be placed with its axis in an approximately vertical position with the welding groove in an approximately horizontal plane. (Illustrated in Fig. 21 (*b*).)

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* To avoid misleading results it is desirable that the base material used in the qualification of a procedure contain amounts of carbon, manganese, chromium, molybdenum and other alloys approaching the maximum quantities of these elements which may be present in the materials that will be welded in actual construction.

(*c*) *Fillet Welds*

In making the tests to qualify fillet welds in plate, the test plates shall be welded in the positions outlined below. (If fillet welds are to be made in pipe, they shall be qualified by tests made in plate unless other tests are specifically provided for by a governing Code.)

(*1*) *Flat Position*—The test plates shall be so placed that each fillet weld is deposited with its axis approximately horizontal and its throat approximately vertical. (See Fig. 2 (*a*).)

(*2*) *Horizontal Position*—The test plates shall be so placed that each fillet weld is deposited on the upper side of the horizontal surface and against the vertical surface. (See Fig. 2 (*b*).)

(*3*) *Vertical Position*—Each fillet weld shall be made vertically. (See Fig. 2 (*c*).)

(*4*) *Overhead Position*—The test plates shall be so placed that each fillet weld is deposited on the under side of the horizontal surface and against the vertical surface. (See Fig. 2 (*d*).)

NOTE: The above arrangement of test plates refers only to the making of the fillet welds. The closing weld between fillet welds in the fillet-weld-soundness test may be made in any position.

105. Number of Test Welds Required

(*a*) *Groove Welds in Plate or Pipe*

For groove welds in material up to and including $^3/_4$ in. thick, one test weld shall be made in material $^3/_8$ in. thick* for each procedure and position to be used in construction, except that if the construction involves welding of material over $^3/_4$ in. thick, a test weld shall be made in material of the maximum thickness* to be used in construction for each procedure and position, but which need not exceed 1 in.* If a test is made in the maximum or 1 in. thickness, no test need be made in the $^3/_8$ in. thickness. In the case of pipe, the nominal diameter of the pipe used for the test weld shall not be less than 6 in.

(*b*) *Fillet Welds*

For fillet welds two longitudinal or two transverse shear test welds shall be made for each procedure and position to be used in construction. For each type of test weld, one shall be made with the maximum size single-pass fillet weld and one with the minimum size multiple-pass fillet weld that will be used in construction. In addition, one test weld for the free-bend and fillet-weld-soundness tests shall be made with the maximum size single-pass fillet weld (not over $^3/_8$ in.) that will be used in construction for each procedure and position to be used in construction.

106. Welding Procedure

The welding procedure shall comply in all respects with the Procedure Specification.

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* In the case of pipe, the wall thickness may vary + or $-12^1/_2$ per cent from that indicated.

107. Test Specimens—Number, Type and Preparation

(a) *Groove Welds*

For groove welds in plate the method of preparing the specimens shall be in accordance with the figures referred to in Table 1 and the number of tests required shall be as given in the table. The test specimens shall be removed in the order given in Figs. 10 and 11.

For groove welds in pipe the method of preparing the specimens shall be in accordance with the figures referred to in Table 2 and the number of tests required shall be as given in the table. The test specimens shall be removed in the order given in Figs. 15 and 16.

TABLE 1—PROCEDURE QUALIFICATION TESTS FOR GROOVE WELDS IN PLATE

Maximum Thickness to Be Welded in Construction	Test Plate Thickness	Number and Type of Tests Required				
		Reduced-Section Tension. (See Fig. 6)	Free-Bend. (See Fig. 7)	Root-Bend. (See Fig. 8)	Face-Bend. (See Fig. 8)	Side-Bend. (See Fig. 9)
Up to and including $^3/_4$ in.	$^3/_8$ in.	2	2	2	2	..
Over $^3/_4$ in.	Maximum, but need not exceed 1 in.	2	2	..	..	4

TABLE 2—PROCEDURE QUALIFICATION TESTS FOR GROOVE WELDS IN PIPE

Maximum Thickness to Be Welded in Construction	Test Pipe Wall Thickness	Number and Type of Tests Required				
		Reduced-Section Tension. (See Fig. 12)	Free-Bend. (See Fig. 13)	Root-Bend. (See Fig. 14)	Face-Bend. (See Fig. 14)	Side-Bend. (See Fig. 9)
Up to and including $^3/_4$ in.	$^3/_8$ in.	2	2	2	2	..
Over $^3/_4$ in.	Maximum, but need not exceed 1 in.	2	2	..	..	4

(b) *Fillet Welds*

The longitudinal shear test specimens shall be welded as shown in Fig. 3 and prepared for testing as shown in Fig. 17. The transverse shear test specimens shall be made as shown in Fig. 4.

The test weld for the free-bend and soundness tests shall be made as shown in Fig. 5. From the test weld there shall be taken two free-bend test specimens, which shall be prepared for testing as shown in Fig. 7, and two fillet-weld-soundness test specimens as shown in Fig. 20.

108. Method of Testing Specimens

(*a*) *Reduced-Section Tension Specimens*

Before testing, the least width and corresponding thickness of the reduced section shall be measured in inches. The specimen shall be ruptured under tensile load and the maximum load in pounds shall be determined. The cross-sectional area shall be obtained as follows: cross-sectional area = width × thickness. The tensile strength in pounds per sq. in. shall be obtained by dividing the maximum load by the cross-sectional area.

(*b*) *Free-Bend Test Specimens*

The gage lines indicated in Fig. 7 shall be lightly scribed on the face of the weld. The gage length (distance between gage lines) shall be approximately $^1/_8$ in. less than the width of the face of the weld, and shall be measured in inches to the nearest 0.01 in.

Each specimen may be bent initially by the use of a fixture complying with the requirements of Fig. 18. The surface of the specimen containing the gage lines shall be directed toward the supports. The weld shall be at midspan of both the supports and the loading block. Alternatively, the initial bend may be made by holding each specimen in the jaws of a vise with one-third the length of the specimen projecting from the jaws, then bending the specimen away from the gage lines through an angle of from 30 to 45° by blows of a hammer. The other end of the specimen shall be bent in the same way. In order that the final bend shall be centered on the weld, the initial bends shall be symmetrical with respect to the weld, and both ends shall be bent through the same angle. The initial bend may also be started at the weld by placing the specimen in the guided-bend test jig shown in Fig. 19.

Compressive forces shall be applied to the ends of the specimen, continuously decreasing the distance between the ends. (Any convenient means such as a vise or a testing machine may be used for the final bend.) When a crack or other open defect exceeding $^1/_{16}$ in.* in any direction appears on the convex face of the specimen, the load shall immediately be removed. If no crack appears, the specimen shall be bent double. Cracks occurring on the corners of the specimen during testing shall not be considered.

The elongation shall be determined by measuring the minimum distance between the gage lines, along the convex surface of the weld, to the nearest 0.01 in. and subtracting the initial gage length. The per cent elongation shall be obtained by dividing the elongation by the initial gage length and multiplying by 100.

(*c*) *Root-, Face-, Side-Bend and Fillet-Weld-Soundness Specimens*

Each specimen shall be bent in a jig having the contour shown in Fig. 19, and otherwise substantially in accordance with that figure. Any convenient means may be used for moving the male member with relation to the female member.

The specimen shall be placed on the female member of the jig with the weld at midspan. Face-bend specimens shall be placed with the face of the weld directed toward the gap; root-bend and fillet-weld-soundness specimens shall be placed with the root of the weld directed toward the gap; side-bend specimens shall be placed with that side showing the greater

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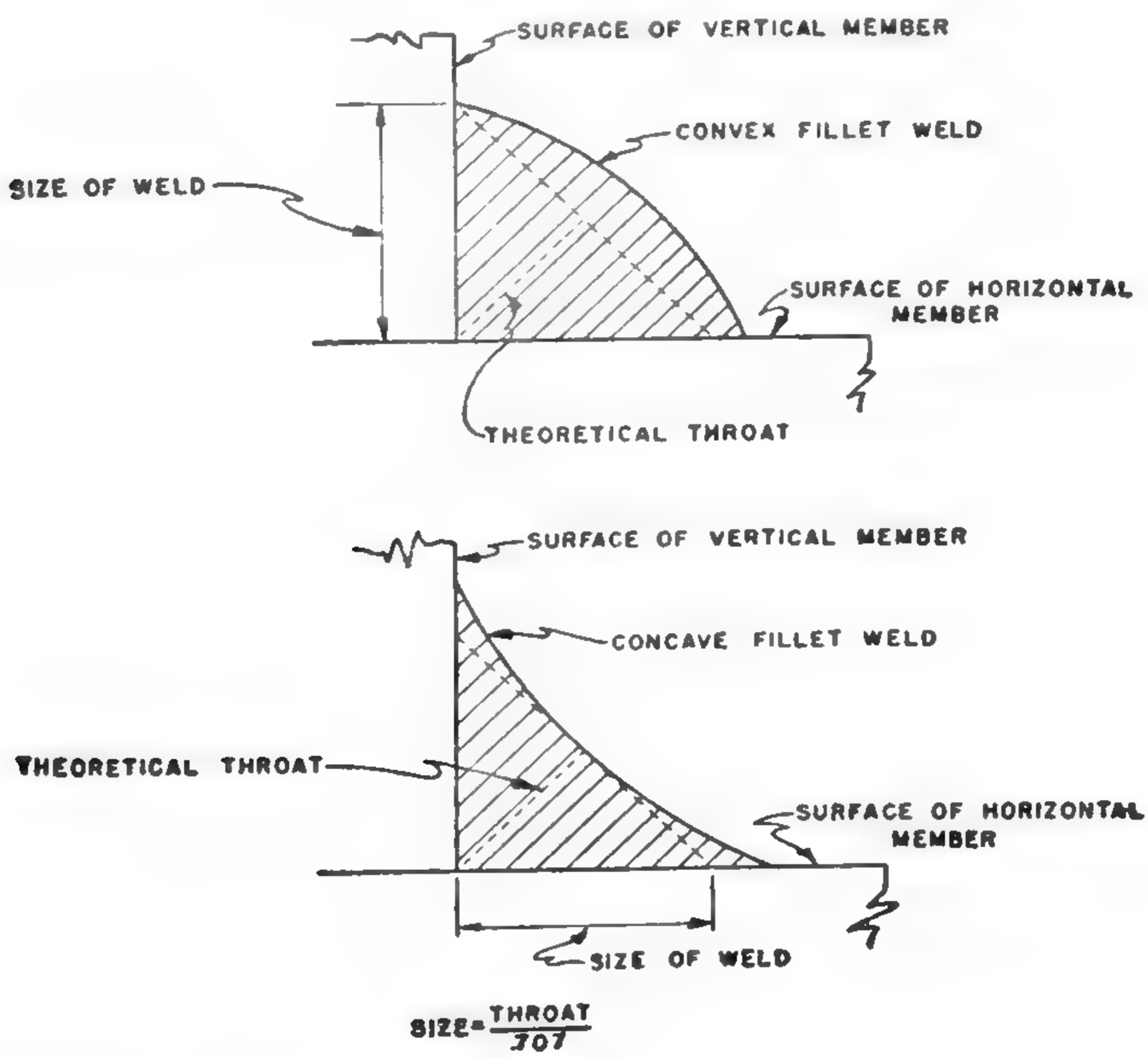
* See Note I on page 1480.

defects, if any, directed toward the gap. The two members of the jig shall be forced together until the curvature of the specimen is such that a $^1/_{32}$ in. diameter wire cannot be passed between the curved portion of the male member and the specimen. The specimen shall then be removed from the jig.

(d) Longitudinal and Transverse Shear Test Specimens

Before testing, the length of the individual welds shall be measured in inches and if any weld varies by more than $^1/_{16}$ in. from the length specified in Figs. 4 and 17, then the length of each weld and its location shall be recorded. The average size of the fillet welds shall also be recorded. The specimen shall be ruptured under tensile load and the maximum load in pounds shall be determined. The shearing strength of the welds in pounds per linear inch shall be obtained by dividing the maximum force by the sum of the lengths of the welds which ruptured. The shearing strength of the welds in pounds per sq. in. shall be obtained by dividing the shearing strength in pounds per linear inch by the average theoretical throat dimension of the welds in inches.

NOTE: The size and theoretical throat dimension of a fillet weld shall be defined as illustrated in the sketch below. The size of a fillet weld is the leg length of the largest inscribed isosceles right triangle. The theoretical throat dimension may be obtained by multiplying the size of the fillet weld by 0.707.



109. Test Results Required

The requirements for the test results shall be as follows:

(*a*) *Reduced-Section Tension Test*

The tensile strength shall be not less than 100 per cent of the minimum of the specified tensile range of the base material used. (See Notes I and III.)

(*b*) *Free-Bend Test*

The elongation shall be not less than 30 per cent for stress-relieved welds nor less than 25 per cent for non-stress-relieved welds. (See Notes I and III.)

(*c*) *Root-, Face-, Side-Bend and Fillet-Weld-Soundness Tests*

The convex surface of the specimen shall be examined for the appearance of cracks or other open defects. Any specimen in which a crack or other open defect is present after the bending, exceeding $^1/_8$ in. measured in any direction, shall be considered as having failed. Cracks occurring on the corners of the specimen during testing shall not be considered. (See Notes I and III.)

(*d*) *Longitudinal or Transverse Shear Test*

For the longitudinal shear test specimen the shearing strength of the welds in pounds per square inch shall be not less than $^2/_3$ of the minimum of the specified tensile range of the base material. For the transverse shear test specimen the shearing strength of the welds in pounds per sq. in. shall be not less than $^7/_8$ of the minimum of the specified tensile range of the base material. (See Notes I, II and III.)

NOTE I: These values as set forth shall apply where no Code is in effect, or where an agreement to use other values has not been made between the purchaser and vendor.

NOTE II: These values are applicable only to low carbon, non-alloy steels. For other materials, the values shall be a matter of agreement between the purchaser and vendor.

NOTE III: The test results specified are not likely to be attained with the metal arc process when using bare or lightly coated electrodes. For such processes it is recommended that the governing Code adopt the following requirements for the test results:

a. Reduced-Section Tension Test—The tensile strength shall be not less than 85 per cent of the minimum of the specified tensile range of the base material used.

b. Free-Bend Test—The elongation shall be not less than 10 per cent.

c. Root-, Face-, Side-Bend and Fillet-Weld-Soundness Tests—The specimen shall be considered as having passed if (1) no crack or other open defect exceeding $^1/_8$ in. measured in any direction is present in the weld metal or between the weld and base material after the bending, or (2) the specimen has cracked or fractured and the fractured surface shows complete penetration through the entire thickness of the weld, and absence of slag inclusions and porosity to the extent that there are no gas pockets or slag inclusions exceeding $^1/_{16}$ in. in greatest dimension and the sum of the greatest dimension of all such defects in any square inch of weld metal area does not exceed $^3/_8$ in. (If necessary, the specimen shall be broken apart to permit examination of the fracture.)

d. Longitudinal or Transverse Shear Test—For the longitudinal shear test specimen the shearing strength of the welds in pounds per square inch shall be not less than $^2/_3$ of the minimum of the specified tensile range of the base material. For the transverse shear test specimen the shearing strength of the welds in pounds per sq. in. shall be not less than $^7/_8$ of the minimum of the specified tensile range of the base material.

110. Records

Records of the test results shall be kept by the manufacturer or contractor and shall be available to those authorized to examine them.

PART II—OPERATOR QUALIFICATION

201. Limitation of Variables

For the qualification of an operator the following rules shall apply. If certain changes are made in a Procedure Specification, operator requalification may be required in accordance with Article 101 (*b*).

202. Types of Tests Required

The qualification tests described herein are specially devised tests to determine the operator's ability to produce sound welds, and may or may not conform in every detail to the requirements of the Procedure Specification. It is not intended that the practices required in the qualification tests shall be used as a guide for welding during actual construction. The latter shall be performed in accordance with the requirements of the Procedure Specification.

The tests used for operator qualification are as follows:

(*a*) *For Groove Welds*

(1) Root-Bend Test
(2) Face-Bend Test
(3) Side-Bend Test

(*b*) *For Fillet Welds*

Fillet-Weld-Soundness Test

203. Base Material and Its Preparation

(*a*) The base material shall comply with the specification for one of the materials listed in the Procedure Specification. For all types of welded joints the length of the weld and the dimensions of the base material shall be such as to provide sufficient material for the test specimens called for hereinafter.

(*b*) For groove welds in plate or pipe where the thickness of the material for the tests as specified in Article 205 (*a*) is $^{3}/_{8}$ in., the preparation of the base material for welding shall be for a single-V groove butt joint meeting the requirements of Fig. 22, except that in the case of oxyacetylene welding the joint preparation may be in accordance with Fig. 24.

(*c*) For groove welds in plate or pipe where the thickness of the material as specified in Article 205 (*a*) exceeds $^{3}/_{8}$ in., the preparation of the base material for welding shall be for a single-V groove butt joint meeting the requirements of Fig. 23, except that in the case of oxyacetylene welding the joint preparation may be in accordance with Fig. 25.

(*d*) For fillet welds the preparation of the base material for welding shall be as shown in Fig. 26. Pipe with a nominal diameter of not less than 6 in. may be used in lieu of plate.

204. Position of Test Welds

(*a*) *Groove Welds*

For the purpose of determining the ability of an operator to make groove welds in various positions in plate or pipe the following positions for test are required.

Test Position 1G

Plates placed in an approximately horizontal plane and the weld metal deposited from the upper side, or a pipe placed with its axis in an approximately horizontal plane with the welding groove in an approximately vertical plane, the pipe being rolled while the weld is deposited within the top quadrant and from the outside of the pipe. (See Fig. 21 (*a*).) This test made either in plate or pipe will qualify the operator for flat position welds in plate and for pipe in the horizontal rolled position. (See Fig. 1 (*a*).)

Test Position 2G

Plates placed in an approximately vertical plane with the welding groove in an approximately horizontal plane, or a pipe placed with its axis in an approximately vertical plane with the welding groove in an approximately horizontal plane. (See Fig. 21 (*b*).) This test made either in plate or pipe will qualify the operator for flat and horizontal welds in plate and for pipe in the horizontal rolled and vertical fixed positions. (See Fig. 1 (*a*).)

Test Position 3G

Plates placed in an approximately vertical plane with the welding groove approximately vertical. (See Fig. 21 (*c*).) This test will qualify the operator for flat and vertical welds in plate and for pipe in the horizontal rolled position. (See Fig. 1 (*a*).)

Test Position 4G

Plates placed in an approximately horizontal plane and the weld metal deposited from the under side. (See Fig. 21 (*d*).) This test will qualify the operator for flat, and overhead welds in plate and for pipe in the horizontal rolled position.

Test Position 5G

A pipe or plate box placed with its axis in an approximately horizontal plane with the welding groove in an approximately vertical plane. The pipe or box shall not be rolled or turned during welding, thus requiring the operator to deposit weld metal from the flat, vertical and overhead positions. (See Fig. 21 (*e*).) This test made either in pipe or a plate box will qualify the operator for welds made in plate in the flat, vertical and overhead positions, and in pipe in the horizontal rolled and horizontal fixed positions. (See Fig. 1 (*a*).)

If a welding operator is tested in Position 2G he need not be tested in Position 1G. If a welding operator is tested in Position 3G he need not be tested in Position 1G. If a welding operator is tested in Position 4G he need not be tested in Position 1G. If a welding operator is tested in Position 5G he need not be tested in Position 1G, 3G or 4G.

(*b*) *Fillet Welds*

For the purpose of determining the ability of an operator to make fillet welds in various positions the following positions for test are required:

Test Position 1F

Plates placed in such position that each weld is deposited with its axis approximately horizontal and with its throat approximately vertical. (See Fig. 27 (*a*).) This test will qualify the operator for flat fillet welds. (See Fig. 1 (*b*).)

Test Position 2F

Plates or pipe placed in such position that each weld is deposited on the upper side of the horizontal surface and against the vertical surface. (See Fig. 27 (*b*).) This test, made either in plate or pipe, will qualify the operator for flat and horizontal fillet welds. (See Fig. 1 (*b*).)

Test Position 3F

Plates or pipe placed in such position that each weld is made vertically. (See Fig. 27 (*c*).) This test, made either in plate or pipe, will qualify the operator for flat, horizontal and vertical fillet welds. (See Fig. 1 (*b*).)

Test Position 4F

Plates or pipe placed in such position that each weld is deposited on the under side of the horizontal surface and against the vertical surface. (See Fig. 27 (*d*).) This test, made either in plate or pipe, will qualify the operator for flat, horizontal and overhead fillet welds. (See Fig. 1 (*b*).)

NOTE: The above arrangement of test plates or pipe refers only to the making of the fillet weld. The closing weld between fillet welds in the fillet-weld-soundness test may be made in any position. See Fig. 27 (*e*).

If a welding operator is tested in Position 2F he need not be tested in Position 1F. If a welding operator is tested in Position 3F he need not be tested in Position 1F or 2F. If a welding operator is tested in Position 4F he need not be tested in Position 1F or 2F.

205. Number of Test Welds Required

(*a*) *Groove Welds in Plate and Pipe*

For groove welds in material up to and including $^3/_4$ in. thick* one test weld as shown in Fig. 22 (Fig. 24 may be used for oxyacetylene welding) shall be made in material $^3/_8$ in. thick for each position for which the operator is to be qualified as defined by Article 204 (*a*), except that if the construction involves welding of material over $^3/_4$ in. thick* one test weld as shown in Fig. 23 (Fig. 25 may be used for oxyacetylene welding) shall be made for each such position in material of the maximum thickness to be used in construction, but the thickness of the material for the test weld need

* Whereas reference has been made above to the test welds being made in material of a given thickness, it is the intent of these rules that if an operator is qualified to weld in a single groove of a given depth, he is also considered as being qualified for welding double-groove butt joints wherein the depth of the groove from either side does not exceed the depth of the single groove for which he has been qualified.

not exceed 1 in. If a test weld is made in the maximum or 1-in. thickness, no test weld need be made in the $^3/_8$-in. thickness. In the case of pipe, the nominal diameter of the pipe used for the test weld shall not be less than 6 in.

(*b*) *Fillet Welds*

For fillet welds one test weld as shown in Fig. 26 shall be made for each position for which the operator is to be qualified, as defined by Article 204 (*b*).

206. Welding Procedure

The operator shall follow the welding procedure specified by the Procedure Specification except that if the form of the test joint differs from the forms of joint as shown in the Procedure Specification to such a degree that it is necessary, in welding the test joint, to change the electrode or welding rod diameters or the number and arrangement of passes from that called for in the Procedure Specification, such changes shall be permissible.

207. Test Specimens—Number, Type and Preparation

(*a*) *Groove Welds*

For groove welds in plate the method of preparing the specimens shall be in accordance with the figures referred to in Table 3 and the number of tests required shall be as given in the table.

For groove welds in pipe the method of preparing the specimens shall be in accordance with the figures referred to in Table 4 and the number of tests required shall be as given in the table.

If the test weld is made in pipe in Position 1G or 2G, the specimens shall be removed approximately 90° from each other. If the test weld is made in Position 5G, using either a pipe or a plate box, a specimen shall be removed from the top, the bottom and each of the two sides of the test weld; and, if the weld is made in $^3/_8$-in.-thick material, the specimen from the top and one side shall be tested with the face of the weld in tension, and the specimen from the bottom and from the other side shall be tested with the root of the weld in tension.

(*b*) *Fillet Welds*

Two test specimens shall be removed from each test weld and prepared for testing as shown in Fig. 20.

208. Method of Testing Specimens

(*a*) *Root-, Face-, Side-Bend and Fillet-Weld-Soundness Specimens*

Each specimen shall be bent in a jig substantially in accordance with Fig. 19. Any convenient means may be used for moving the male member with relation to the female member.

The specimen shall be placed on the female member of the jig with the weld at midspan. Face-bend specimens shall be placed with the face of the weld directed toward the gap; root-bend and fillet-weld-soundness specimens shall be placed with the root of the weld directed toward the gap; side-bend specimens shall be placed with that side showing the greater defects, if any, directed toward the gap. The two members of the jig shall be forced together until the curvature of the specimen is such that a $^1/_{32}$-

TABLE 3—OPERATOR QUALIFICATION TESTS FOR GROOVE WELDS IN PLATE

Maximum Thickness for Which Operator Is to Be Qualified	Thickness of Material for Test Weld	Number and Type of Tests Required		
		Root-Bend. (See Fig. 8)	Face-Bend. (See Fig. 8)	Side-Bend (See Fig. 9)
Up to and including 3/4 in.	3/8 in.	1	1	..
Over 3/4 in.	Maximum, but need not exceed 1 in.	..	..	2

TABLE 4—OPERATOR QUALIFICATION TESTS FOR GROOVE WELDS IN PIPE

Maximum Thickness for Which Operator Is to Be Qualified	Thickness of Material for Test Weld	Number and Type of Tests Required		
		Root-Bend. (See Fig. 14)	Face-Bend. (See Fig. 14)	Side-Bend. (See Fig. 9)
Up to and including 3/4 in.	3/8 in.	2	2	..
Over 3/4 in.	Maximum, but need not exceed 1 in.	..	..	4

in. diameter wire cannot be passed between the curved portion of the male member and the specimen. The specimen shall then be removed from the jig.

209. Test Results Required

(*a*) *Root-, Face-, Side-Bend and Fillet-Weld-Soundness Tests*

The convex surface of the specimen shall be examined for the appearance of cracks or other open defects. Any specimen in which a crack or other open defect is present after the bending, exceeding 1/8 in. measured in any direction, shall be considered as having failed. Cracks occurring on the corners of the specimen during testing shall not be considered. (See Notes I and II.)

NOTE I: These values as set forth shall apply where no Code is in effect, or where an agreement to use other values has not been made between the purchaser and vendor.

NOTE II: The test results specified are not likely to be attained with the metal arc process when using bare or lightly coated electrodes. For such processes it is recommended that the governing Code adopt the following requirements for the test results:

The specimen shall be considered as having passed if (1) no crack or other open defect exceeding 1/8 in. measured in any direction is present in the weld metal or between the weld and base material after the bending, or (2) the specimen has cracked or fractured and the fractured surface shows complete penetration through the entire thickness of the weld, and absence of slag inclusions and porosity to the extent that there are no gas pockets or slag inclusions exceeding 1/16 in. in greatest dimension and the sum of the greatest dimension of all such defects in any square inch of weld metal area does not exceed 3/8 in. (If necessary, the specimen shall be broken apart to permit examination of the fracture.)

210. Retests

In case an operator fails to meet the requirements of one or more test welds a retest may be allowed under the following conditions:

(*a*) An immediate retest may be made which shall consist of two test

welds of each type on which he failed, all of which shall meet all the requirements specified for such welds.

(*b*) A retest may be made provided there is evidence that the operator has had further training or practice. In this case a complete retest shall be made.

211. Period of Effectiveness

The operator qualification tests herein specified shall be considered as remaining in effect indefinitely unless (1) the welding operator is not engaged in a given process of welding (i.e., arc or gas) for a period of three months or more;* or unless (2) there is some specific reason to question an operator's ability. In case (1) above the requalification test need be made only in the $^3/_8$ in. thickness.

212. Records

Copies of the record for each qualified welding operator shall be kept by the manufacturer or contractor, and shall be available to those authorized to examine them.

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* The intent of this statement is as follows:

An operator who has been qualified for metal arc welding under any given Procedure Specification is not required to requalify for that Procedure unless he has done no metal arc welding for a period of three months or more. In a similar manner the qualification of an operator for gas welding or for carbon arc welding is not considered as having expired unless he has done no gas welding or carbon arc welding, as the case may be, for a period of three months or more.

TABLE 5—GROUPING OF MATERIALS FOR PROCEDURE AND OPERATOR QUALIFICATION*

"P" Number 1—"O" Number 1

Materials in this group shall not have a carbon content exceeding 0.30 per cent, a manganese content exceeding 1.10 per cent, or a silicon content exceeding 0.50 per cent, as determined by ladle analysis. In addition, the carbon content by percentage shall not exceed the value $0.55 - \left(\frac{Mn + Si}{4}\right)$, where Mn is the percentage of manganese and Si is the percentage of silicon.

A. S. T. M. Spec. No.		Name
A-7		Steel for Bridges and Buildings
A-10		Mild Steel Plates
A-30		Boiler and Firebox Steel for Locomotives
A-53		Welded and Seamless Steel Pipe
A-70		Carbon-Steel Plates for Stationary Boilers, etc.
A-78		Low Tensile Strength Carbon Steel Plates of Structural Quality for Welding
A-83		Lap-Welded and Seamless Steel and Lap-Welded Iron Boiler Tubes
A-87	Grade A1	Carbon-Steel and Alloy-Steel Castings for Railroads
	Grade A2	Carbon-Steel and Alloy-Steel Castings for Railroads
A-89		Low Tensile Strength Carbon-Steel Plates of Flange and Firebox Quality
A-105		Forged or Rolled Steel Pipe Flanges for High-Temperature Service
A-106	Grade A	Lap-Welded and Seamless Steel Pipe for High-Temperature Service
	Grade OH	Lap-Welded and Seamless Steel Pipe for High-Temperature Service
A-107	Grade 1	Commercial Quality Hot-Rolled Bar Steels
	Grade 2	Commercial Quality Hot-Rolled Bar Steels
	Grade 3	Commercial Quality Hot-Rolled Bar Steels
	Grade 4	Commercial Quality Hot-Rolled Bar Steels
	Grade 5	Commercial Quality Hot-Rolled Bar Steels
	Grade 17	Commercial Quality Hot-Rolled Bar Steels
A-113		Structural Steel for Locomotives and Cars
A-120		Black Welded and Seamless Steel Pipe, etc. (Galvanized pipe not included)
A-129		Open-Hearth Iron Plates of Flange Quality
A-131		Structural Steel for Ships
A-134		Electric-Fusion-Welded Steel Pipe (Size 30 in. and over)
A-135		Electric-Resistance-Welded Steel Pipe
A-136		Forge-Welded Steel Pipe
A-139		Electric-Fusion-Welded Steel Pipe (8 in. to but not including 30 in. diam.)
A-155		Electric-Fusion-Welded Steel Pipe for High-Temperature and High-Pressure Service
A-178	Grade A	Electric-Resistance-Welded Steel and Open-Hearth Iron Boiler Tubes
	Grade B	Electric-Resistance-Welded Steel and Open-Hearth Iron Boiler Tubes
A-181		Forged or Rolled Steel Pipe Flanges for General Service
A-192		Seamless Steel Boiler Tubes for High-Pressure Service
A-201		Carbon-Silicon Steel Plates of Ordinary Tensile Ranges

* Steels not included in the table require separate procedure and operator qualification except in the case of the so-called low-alloy, high-strength steels. In the latter group of steels separate procedure qualification is required for each change in brand or analysis but "O" Number 1 applies in all cases.

"P" Number 1—"O" Number 1—(*Continued*)

A-215-39T	Grade N-1-W.	Carbon-Steel Castings Suitable for Fusion Welding, etc.
	Grade A-1-W	Carbon-Steel Castings Suitable for Fusion Welding, etc.
	Grade A-2-W	Carbon-Steel Castings Suitable for Fusion Welding, etc.
	Grade A-3-W	Carbon-Steel Castings Suitable for Fusion Welding, etc.
A-216-40T	Grade WCA	Carbon-Steel Castings Suitable for Fusion Welding, etc. (to 850° F.)
A-235-40T	Grade A	Carbon-Steel Forgings for General Industrial Use
	Grade B	Carbon-Steel Forgings for General Industrial Use
	Grade C	Carbon-Steel Forgings for General Industrial Use
A-236-40T	Grade A	Carbon-Steel Forgings for Locomotives and Cars

"P" Number 2—"O" Number 1

A-42	Wrought-Iron Plates
A-72	Welded Wrought-Iron Pipe
A-73	Wrought-Iron Rolled or Forged Blooms and Forgings
A-162	Uncoated Wrought-Iron Sheets
A-207	Rolled Wrought-Iron Shapes and Bars

"P" Number 3—"O" Number 1

Materials in this group shall not have a carbon content exceeding 0.35 per cent, a manganese content exceeding 1.50 per cent, or a silicon content exceeding 0.50 per cent, as determined by ladle analysis. In addition, the carbon content by percentage shall not exceed the value $0.65 - \left(\frac{Mn + Si}{4}\right)$, where Mn is the percentage of manganese and Si is the percentage of silicon.

(Experience has indicated that it is advisable to preheat up to 350° F. when welding the materials included in this group.)

A-7		Steel for Bridges and Buildings
A-30		Boiler and Firebox Steel for Locomotives
A-70		Carbon-Steel Plates for Stationary Boilers, etc.
A-87	Grade B	Carbon-Steel and Alloy-Steel Castings for Railroads
A-95		Carbon-Steel Castings for Valves, Flanges and Fittings for High-Temperature Service
A-105		Forged or Rolled Steel Pipe Flanges for High-Temperature Service
A-106	Grade B	Lap-Welded and Seamless Steel Pipe for High-Temperature Service
A-107	Grade 6	Commercial Quality Hot-Rolled Bar Steels
	Grade 7	Commercial Quality Hot-Rolled Bar Steels
A-131		Structural Steel for Ships
A-178	Grade C	Electric-Resistance-Welded Steel and Open-Hearth Iron Boiler Tubes
A-181		Forged and Rolled Steel Pipe Flanges for General Service
A-201		Carbon-Silicon Steel Plates of Ordinary Tensile Ranges, etc.
A-210		Medium-Carbon Seamless Steel Boiler and Superheater Tubes
A-212		High-Tensile Strength Carbon-Silicon Steel Plates, etc.
A-215-39T	Grade N-2-W	Carbon-Steel Castings Suitable for Fusion Welding, etc.
	Grade BW	Carbon-Steel Castings Suitable for Fusion Welding, etc.
	Grade B-1-W	Carbon-Steel Castings Suitable for Fusion Welding, etc.
	Grade B-2-W	Carbon-Steel Castings Suitable for Fusion Welding, etc.
A-216-40T	Grade WCB	Carbon-Steel Castings Suitable for Fusion Welding, etc (to 850° F.)
A-235-40T	Grade C1	Carbon-Steel Forgings for General Industrial Use
	Grade D	Carbon-Steel Forgings for General Industrial Use
	Grade E	Carbon-Steel Forgings for General Industrial Use
A-236-40T	Grade B	Carbon-Steel Forgings for Locomotives and Cars
	Grade C	Carbon-Steel Forgings for Locomotives and Cars
	Grade D	Carbon-Steel Forgings for Locomotives and Cars

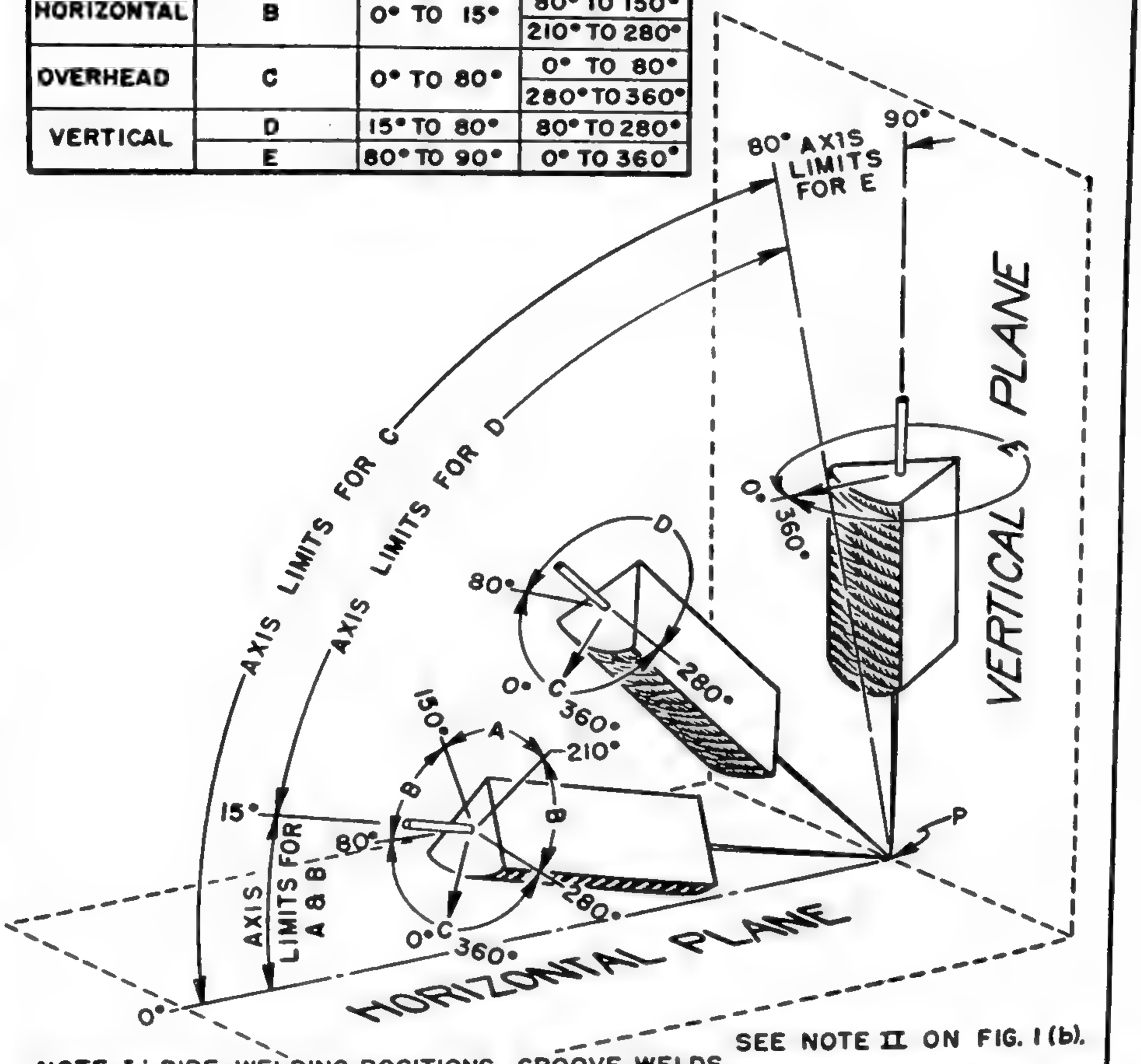
"P" Number 4—"O" Number 1

The carbon content by ladle analysis shall not exceed 0.28 per cent.

A-182	Grade F1	Forged or Rolled Alloy-Steel Pipe Flanges, etc. (from 750-1100° F.)
A-202	Grade A	Cr-Mn-Si Alloy-Steel Plates for Boilers, etc.
A-203	Grade A	Low-Carbon Nickel-Steel Plates for Boilers, etc.
	Grade B	Low-Carbon Nickel-Steel Plates for Boilers, etc.
A-204	Grade A	Molybdenum-Steel Plates for Boilers, etc.
	Grade B	Molybdenum-Steel Plates for Boilers, etc.
	Grade C	Molybdenum-Steel Plates for Boilers, etc.
A-206-40T		Seamless Carbon-Molybdenum Alloy-Steel Pipe for Service at Temperatures of 750–1000° F.
A-209-40T		Seamless Carbon-Molybdenum Alloy-Steel Boiler and Superheater Tubes
A-217	Grade WC1	Alloy-Steel Castings Suitable for Fusion Welding, etc. (750–1100° F.)
	Grade WC2	Alloy-Steel Castings Suitable for Fusion Welding, etc. (750-1100° F.)
A-225		Manganese-Vanadium Steel Plates for Boilers, etc.

TABULATION OF POSITIONS OF GROOVE WELDS

POSITION	DIAGRAM REFERENCE	INCLINATION OF AXIS	ROTATION OF FACE
FLAT	A	0° TO 15°	150° TO 210°
HORIZONTAL	B	0° TO 15°	80° TO 150°
			210° TO 280°
OVERHEAD	C	0° TO 80°	0° TO 80°
			280° TO 360°
VERTICAL	D	15° TO 80°	80° TO 280°
	E	80° TO 90°	0° TO 360°



SEE NOTE II ON FIG. 1(b).

NOTE I: PIPE WELDING POSITIONS - GROOVE WELDS

FOR GROOVE WELDS IN PIPE THE FOLLOWING DEFINITIONS SHALL APPLY.

HORIZONTAL FIXED POSITION: WHEN THE AXIS OF THE PIPE DOES NOT DEVIATE BY MORE THAN 30° FROM THE HORIZONTAL PLANE AND THE PIPE IS NOT ROTATED DURING WELDING.

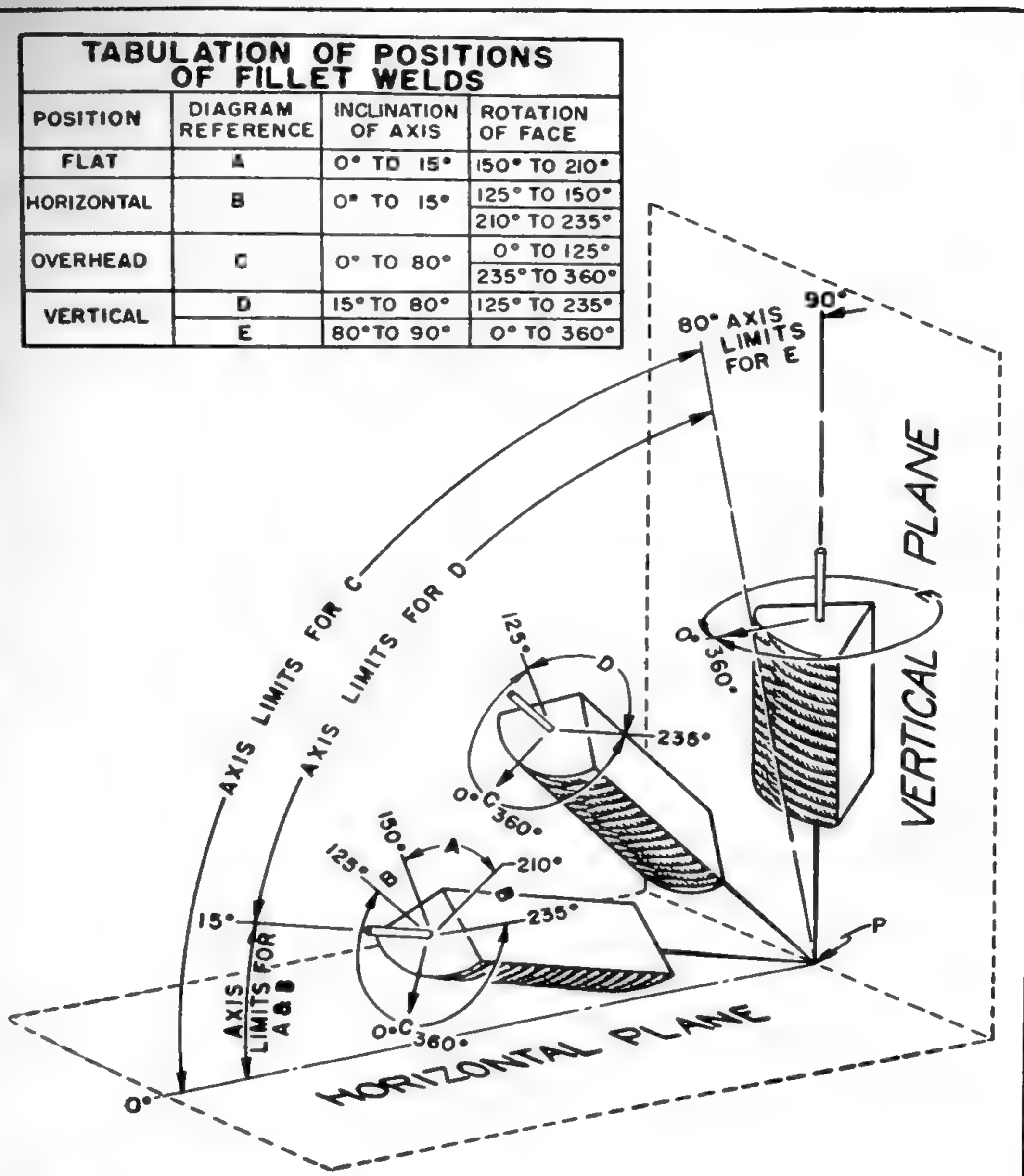
HORIZONTAL ROLLED POSITION: WHEN THE AXIS OF THE PIPE DOES NOT DEVIATE BY MORE THAN 30° FROM THE HORIZONTAL PLANE, THE PIPE IS ROTATED DURING WELDING, AND THE WELD METAL IS DEPOSITED WITHIN AN ARC NOT TO EXCEED 15° ON EITHER SIDE OF A VERTICAL PLANE PASSING THROUGH THE AXIS OF THE PIPE.

VERTICAL POSITION: WHEN THE AXIS OF THE PIPE DOES NOT DEVIATE BY MORE THAN 10° FROM THE VERTICAL POSITION (THE PIPE MAY OR MAY NOT BE ROTATED DURING WELDING.)*

*POSITIONS IN WHICH THE AXIS OF THE PIPE DEVIATES BY MORE THAN 10° AND LESS THAN 60° FROM THE VERTICAL SHALL BE CONSIDERED INTERMEDIATE, AND SHALL REQUIRE THE PROCEDURE AND OPERATOR TO BE QUALIFIED IN BOTH THE HORIZONTAL FIXED AND THE VERTICAL POSITIONS.

POSITIONS OF GROOVE WELDS
FIGURE 1(a)

TABULATION OF POSITIONS OF FILLET WELDS			
POSITION	DIAGRAM REFERENCE	INCLINATION OF AXIS	ROTATION OF FACE
FLAT	A	0° TO 15°	150° TO 210°
HORIZONTAL	B	0° TO 15°	125° TO 150°
			210° TO 235°
OVERHEAD	C	0° TO 80°	0° TO 125°
			235° TO 360°
VERTICAL	D	15° TO 80°	125° TO 235°
	E	80° TO 90°	0° TO 360°



NOTE 11:

THE HORIZONTAL REFERENCE PLANE IS TAKEN TO LIE ALWAYS BELOW THE WELD UNDER CONSIDERATION.

INCLINATION OF AXIS IS MEASURED FROM THE HORIZONTAL REFERENCE PLANE TOWARD THE VERTICAL.

ANGLE OF ROTATION OF FACE IS MEASURED FROM A LINE PERPENDICULAR TO THE AXIS OF THE WELD AND LYING IN A VERTICAL PLANE CONTAINING THIS AXIS. THE REFERENCE POSITION (0°) OF ROTATION OF THE FACE INVARIABLY POINTS IN THE DIRECTION OPPOSITE TO THAT IN WHICH THE AXIS ANGLE INCREASES. THE ANGLE OF ROTATION OF THE FACE OF WELD IS MEASURED IN A CLOCKWISE DIRECTION FROM THIS REFERENCE POSITION (0°) WHEN LOOKING AT POINT P.

POSITIONS OF FILLET WELDS
FIGURE 1(b)

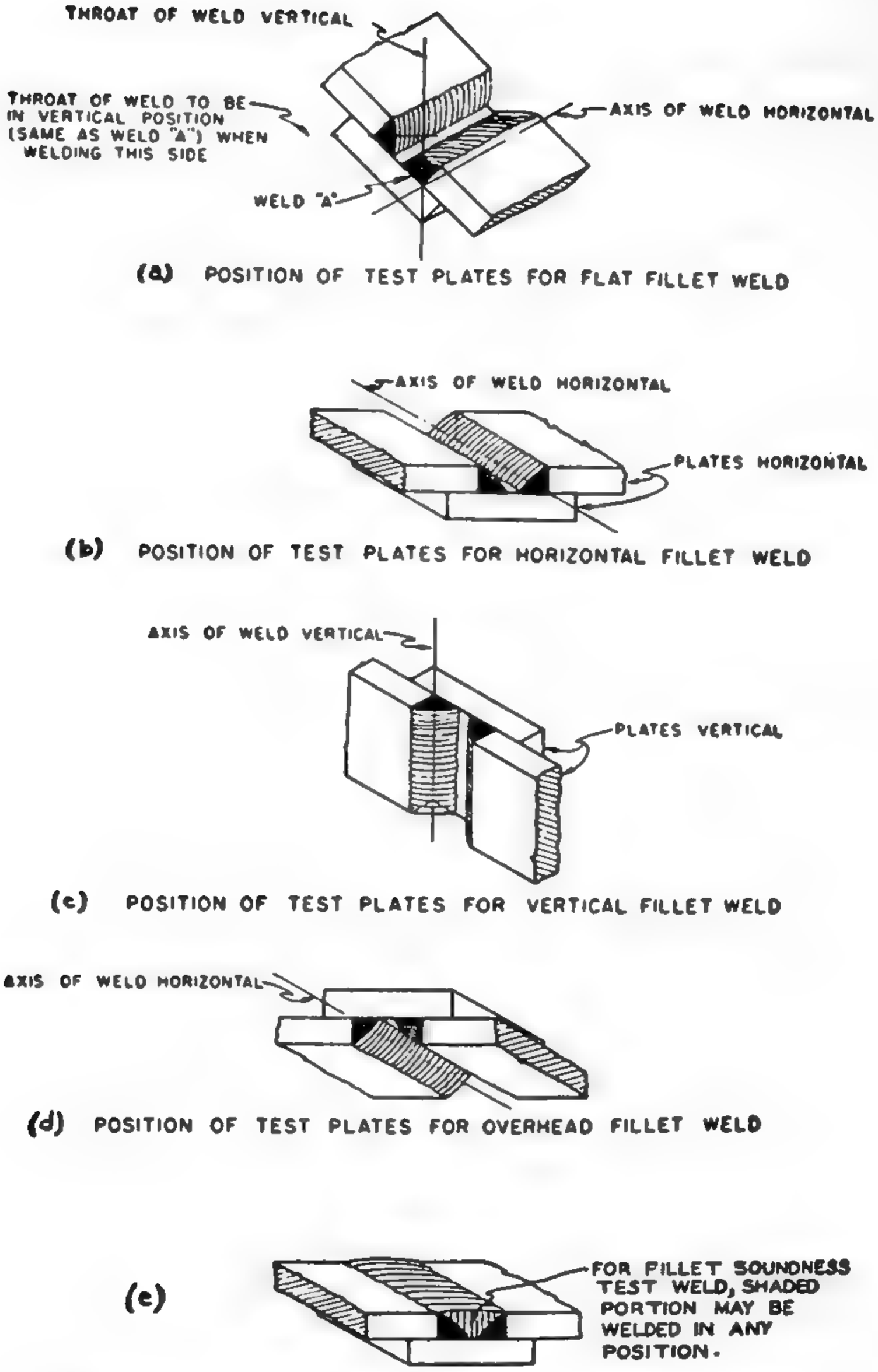
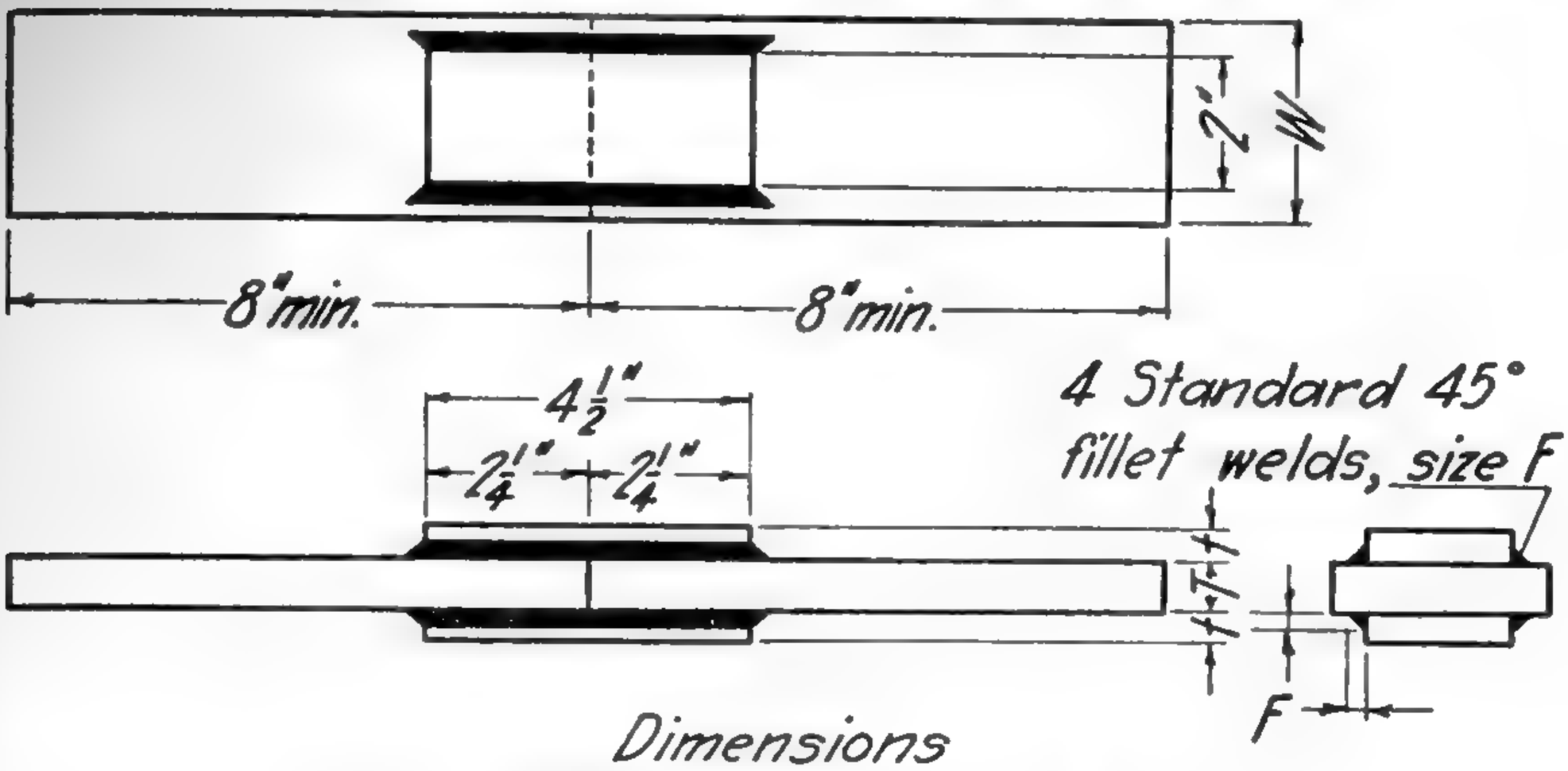


Fig. 2—Positions of Test Plates for Fillet Welds



Dimensions

Size of weld F, in.	1/8	1/4	3/8	1/2
Thickness t, in., min.	3/8	1/2	3/4	1
Thickness T, in.	3/8	3/4	1	1 1/4
Width W, in.	3	3	3	3 1/2

Fig. 3—Longitudinal Fillet-Weld Shearing Specimen After Welding

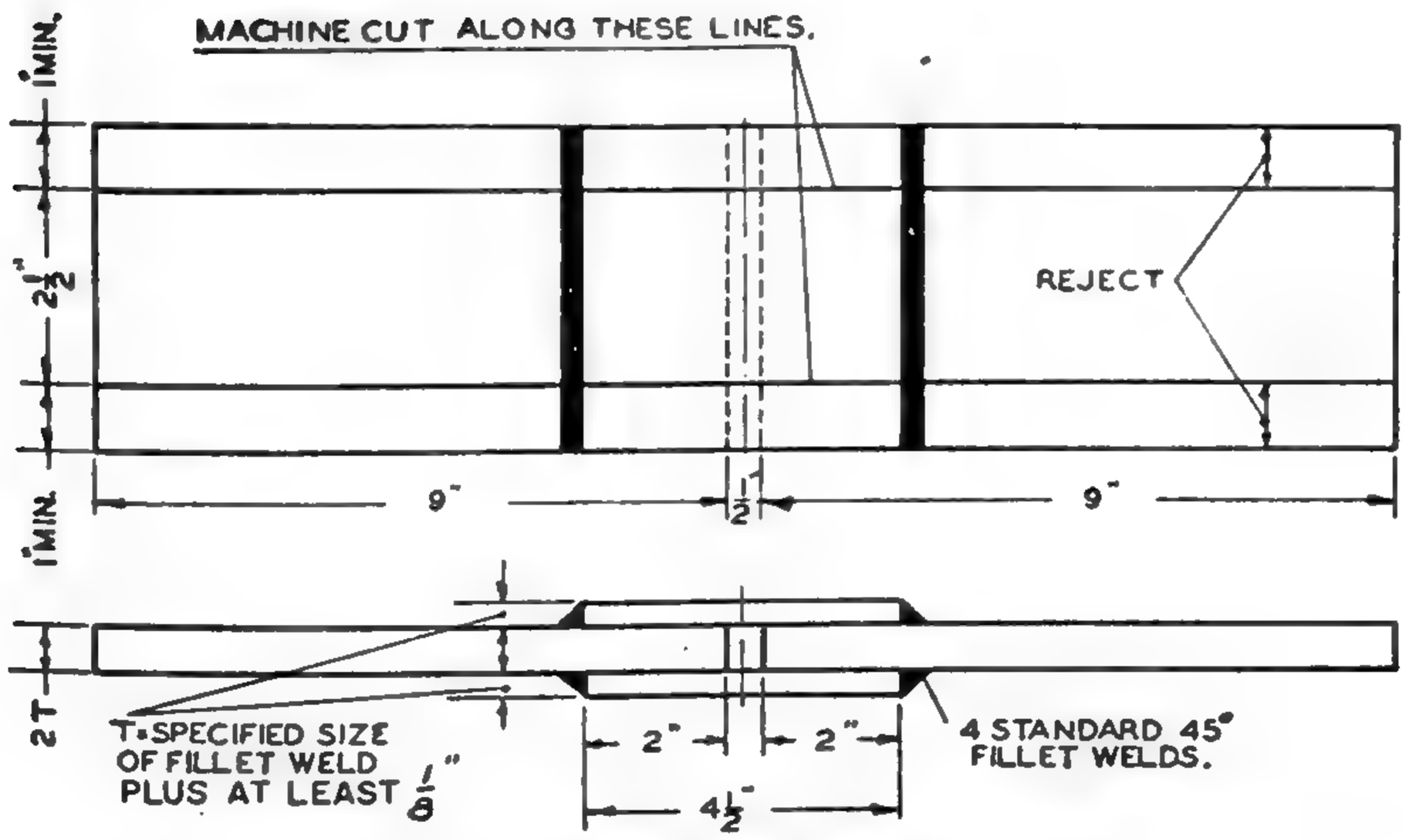


Fig. 4—Transverse Fillet-Weld Shearing Specimen

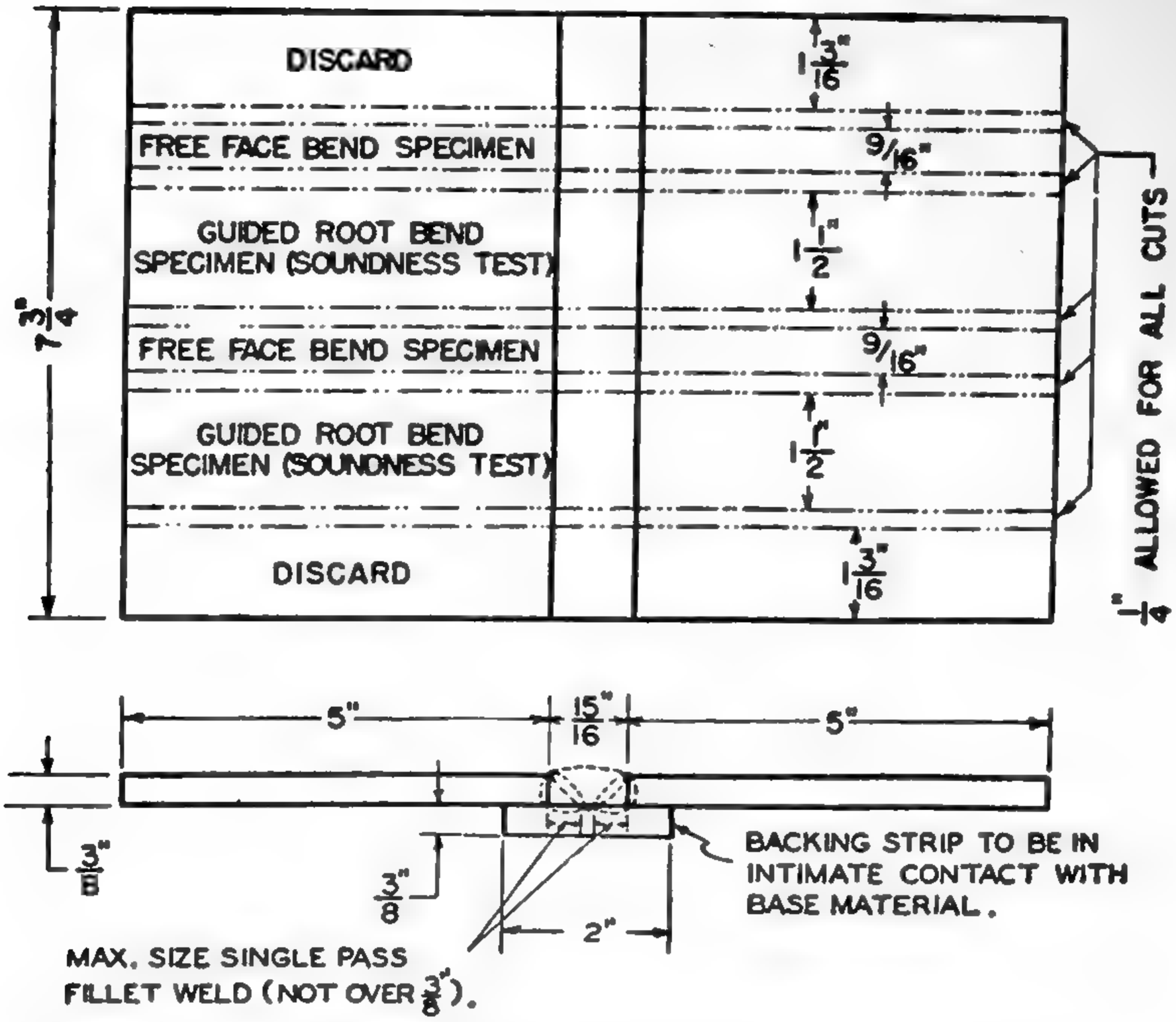


Fig. 5—Test Weld for Free-Bend and Soundness Tests

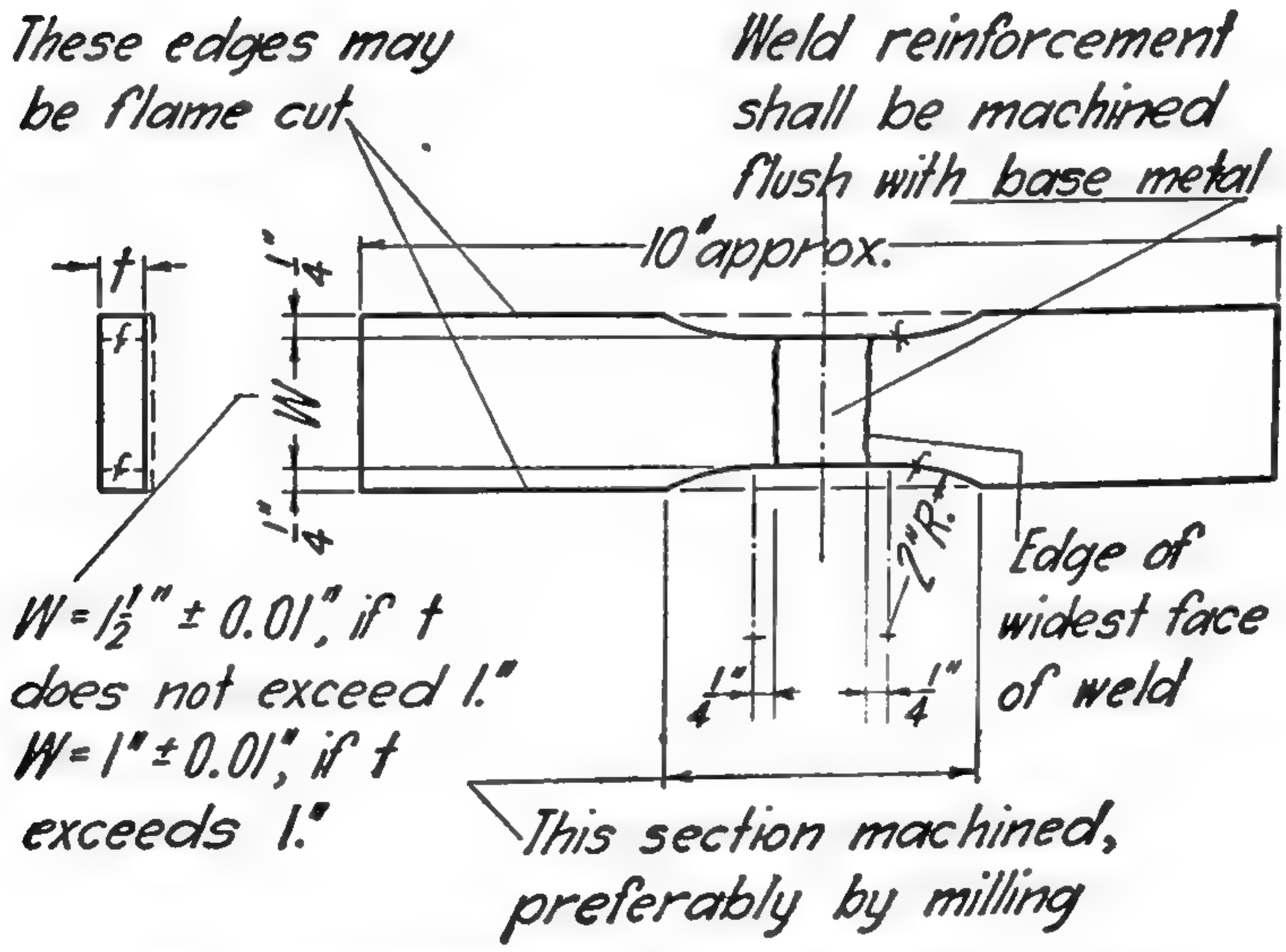
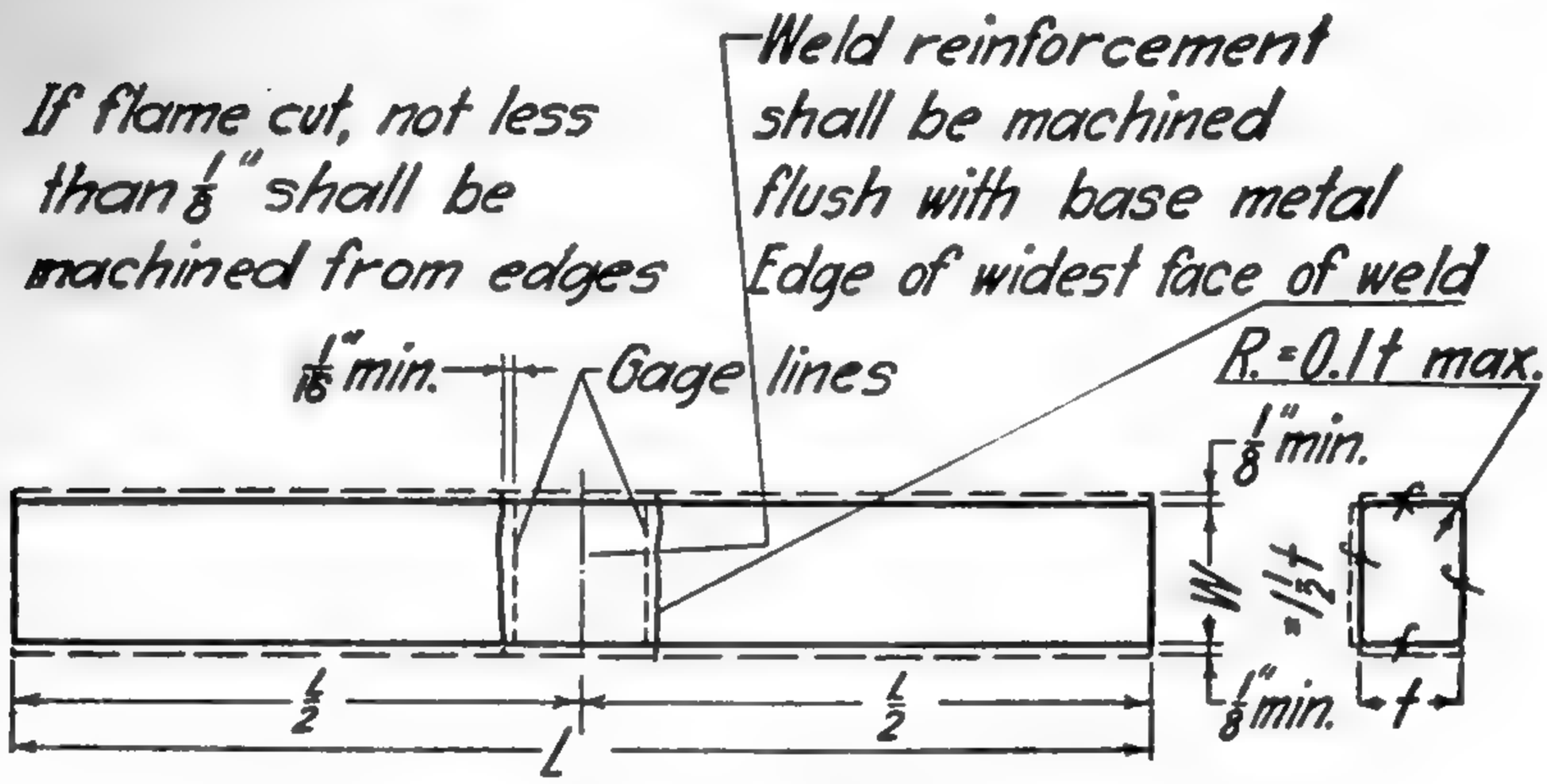


Fig. 6—Reduced-Section Tension Specimen (Plate)

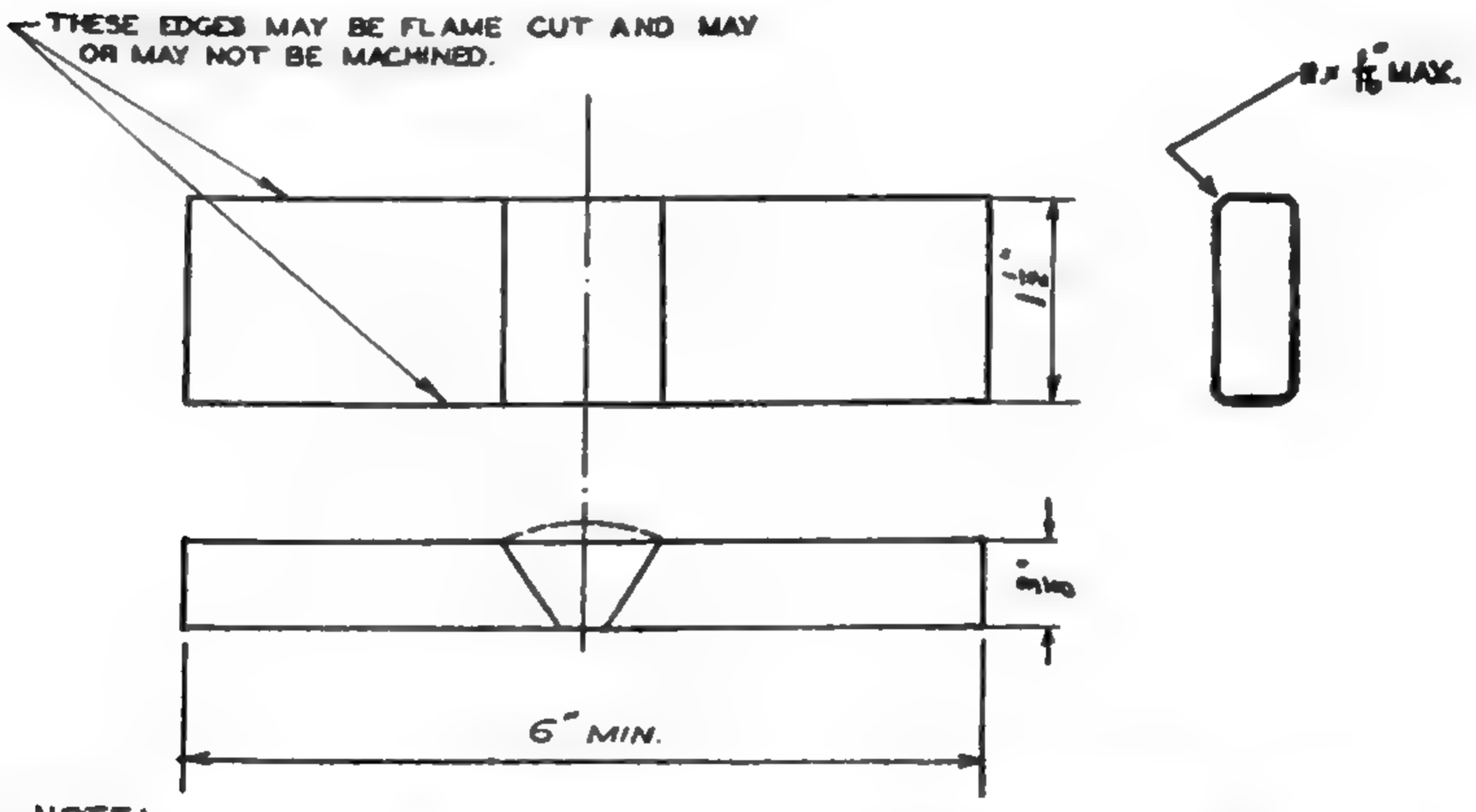


Dimensions

t, in.	3/8	3/4	1	1 1/4	1 1/2	2	2 1/2
W, in.	9/16	1 1/8	1 1/2	1 7/8	2 1/4	3	3 3/4
L min, in.	8	11	12	13 1/2	15	18	21
B* min, in.	1 1/4	2	2	2	2	2	3

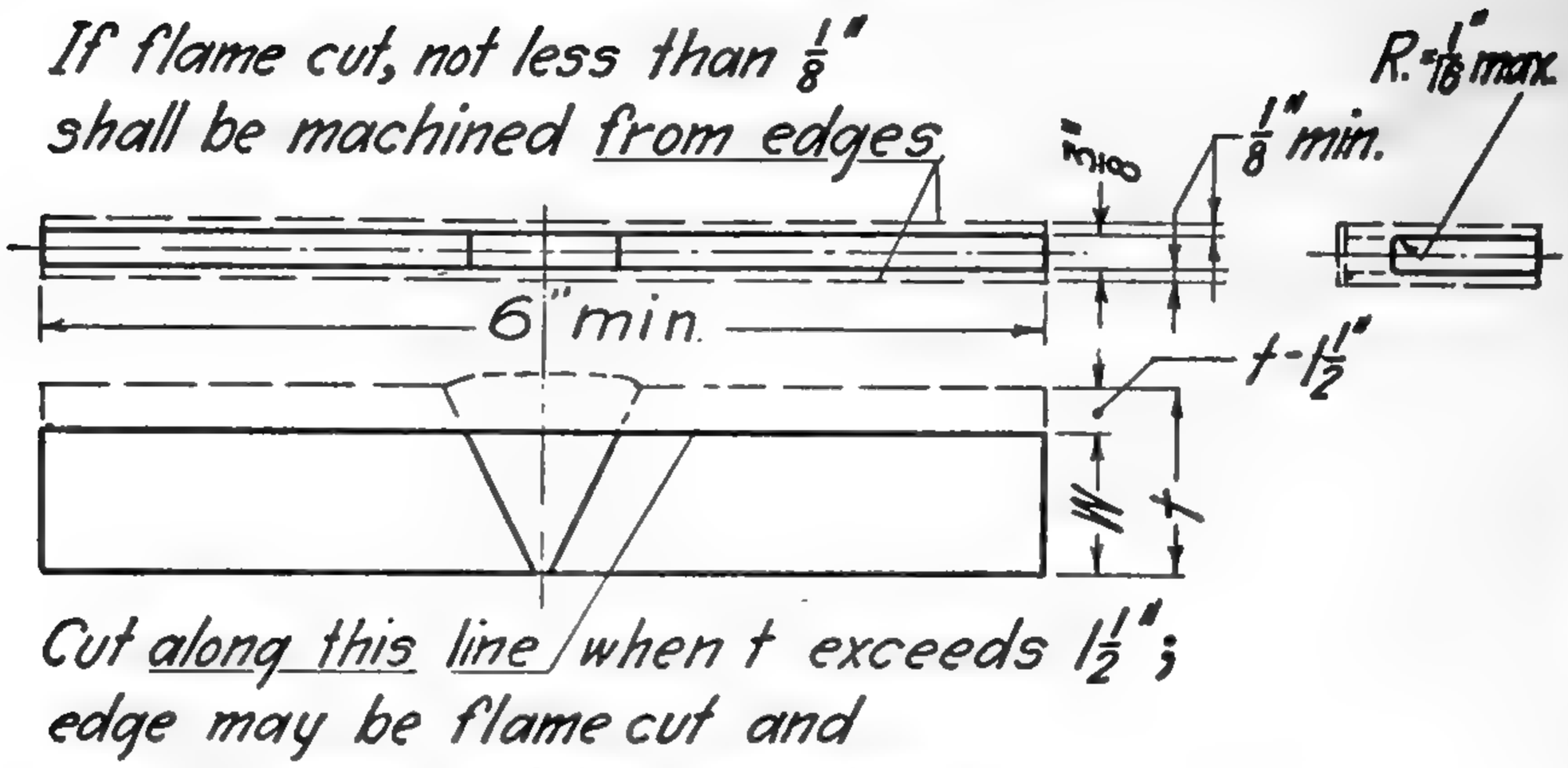
*SEE FIG. 18.
NOTE 1: THE LENGTH L IS SUGGESTIVE ONLY, NOT MANDATORY.
NOTE 2: IF DESIRED, THE EDGES OF THE SPECIMEN MAY BE PREPARED BY MACHINE FLAME CUTTING, FOLLOWED BY ROUNDING OF THE CORNERS WITH A FILE, THOUGH THIS MAY BE A MORE SEVERE TEST.

Fig. 7—Free-Bend Specimen (Plate)



NOTE:
WELD REINFORCEMENT AND BACKING STRIP, IF ANY, SHALL BE REMOVED FLUSH WITH THE SURFACE OF THE SPECIMEN. IF A RECESSED STRIP IS USED THIS SURFACE OF THE SPECIMEN MAY BE MACHINED TO A DEPTH NOT EXCEEDING THE DEPTH OF THE RECESS TO REMOVE THE STRIP, EXCEPT THAT IN SUCH CASES THE THICKNESS OF THE FINISHED SPECIMEN SHALL BE THAT SPECIFIED ABOVE.

Fig. 8—Face- and Root-Bend Specimens (Plate)



t, in.	W, in.
3/4" to 1 1/2"	t
> 1 1/2"	1 1/2"

Fig. 9—Side-Bend Specimen

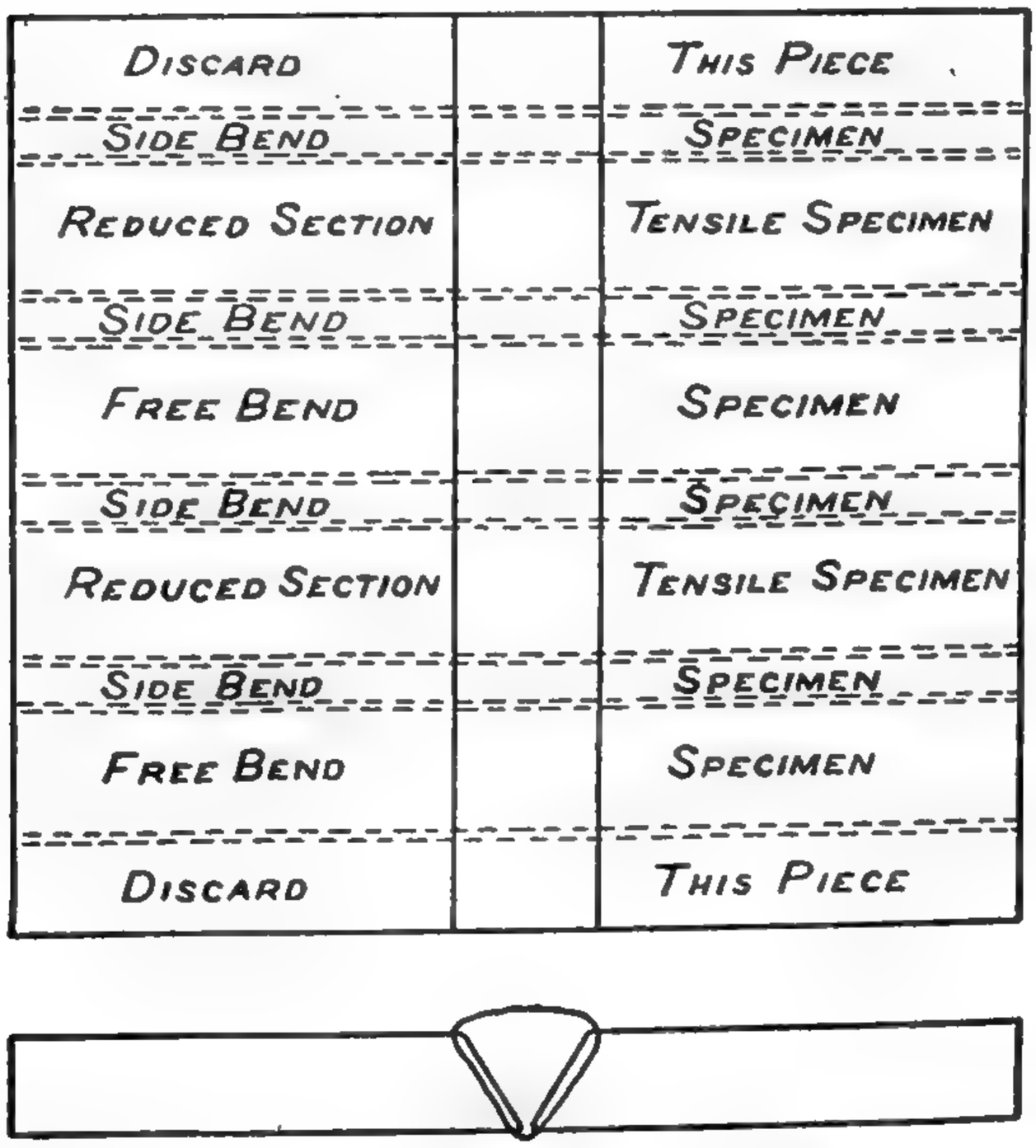


Fig. 10—Order of Removal of Test Specimens from Welded Test Plate (for Plate Over 3/4 In. Thick)

DISCARD		THIS PIECE
REDUCED SECTION		TENSILE SPECIMEN
ROOT BEND		SPECIMEN
FREE BEND		SPECIMEN
FACE BEND		SPECIMEN
ROOT BEND		SPECIMEN
FREE BEND		SPECIMEN
FACE BEND		SPECIMEN
REDUCED SECTION		TENSILE SPECIMEN
DISCARD		THIS PIECE

Fig. 11—Order of Removal of Test Specimens from Welded Test Plate (for Plate 3/8 In. Thick)

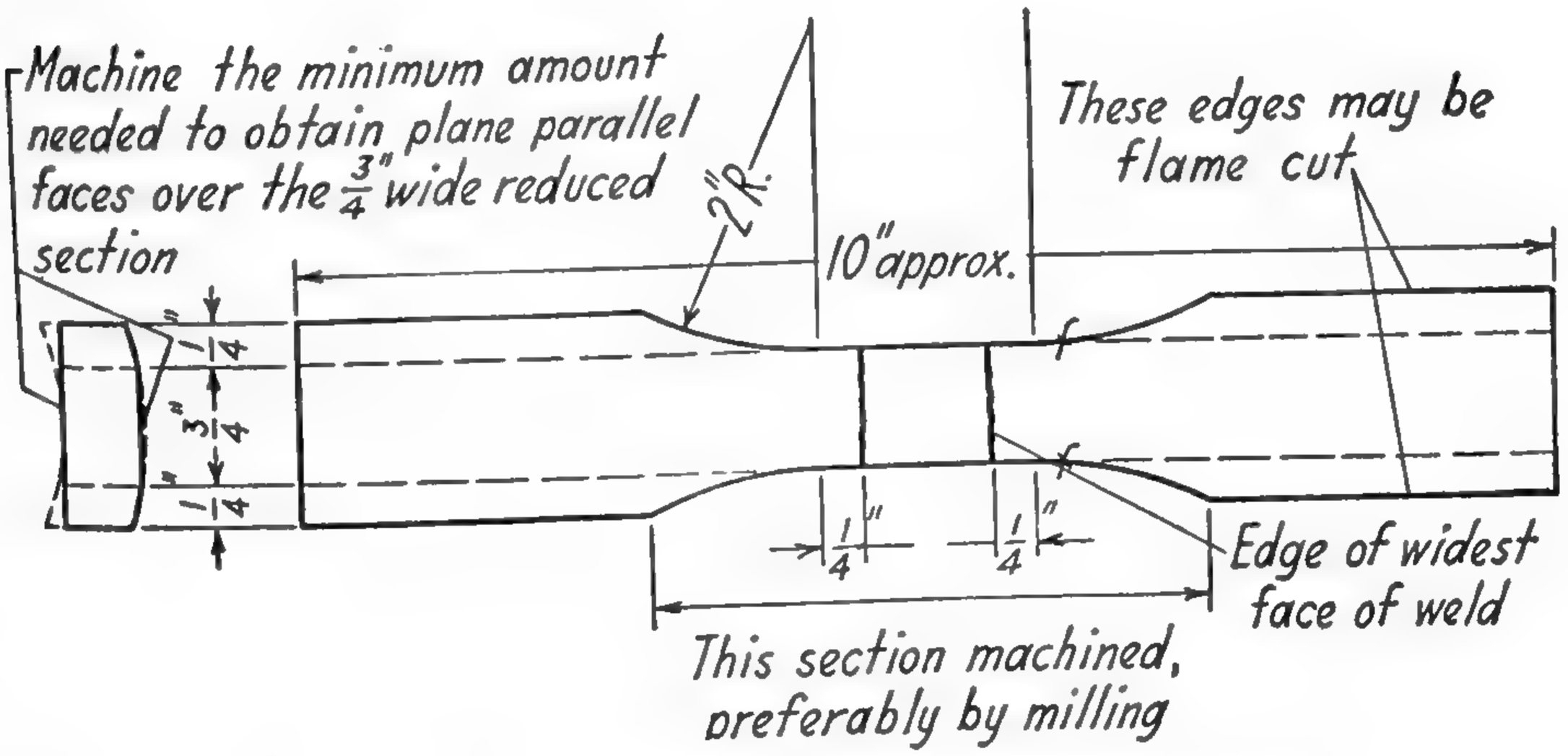


Fig. 12—Reduced Section Tension Specimen (Pipe)

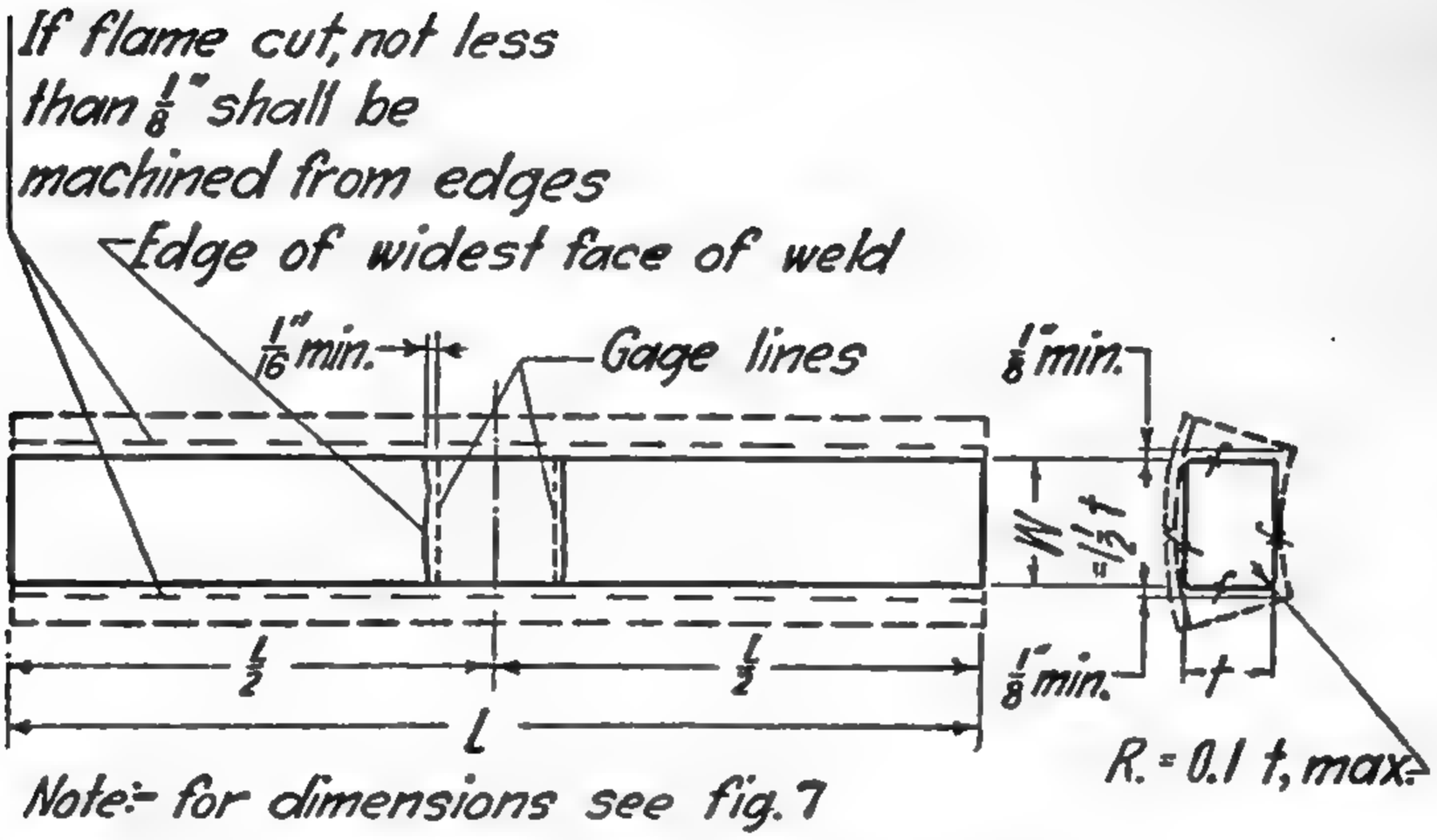
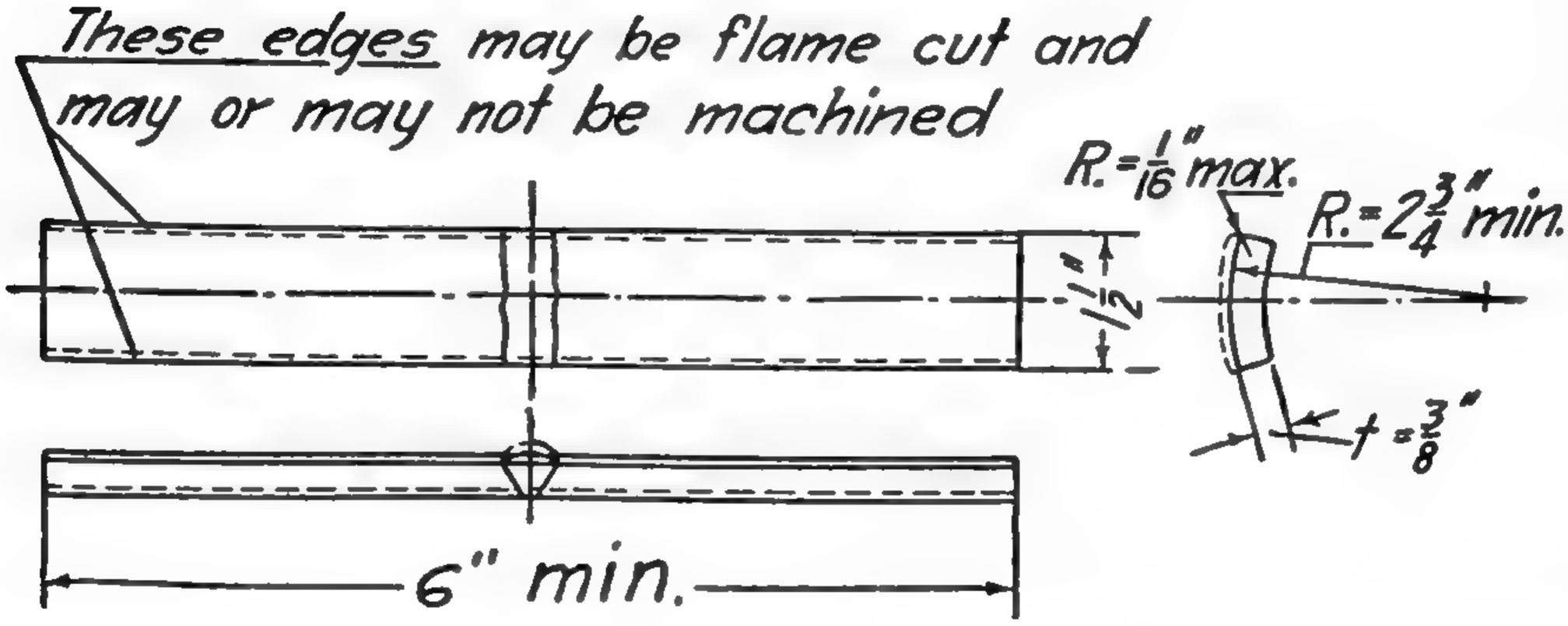


Fig. 13—Free-Bend Specimen (Pipe)



NOTE: Weld reinforcement and backing ring, if any, shall be removed flush with the surface of the specimen. If a recessed ring is used, this surface of the specimen may be machined to a depth not exceeding the depth of the recess to remove the ring, except that in such cases the thickness of the finished specimen shall be that specified above

Fig. 14—Face- and Root-Bend Specimens (Pipe)

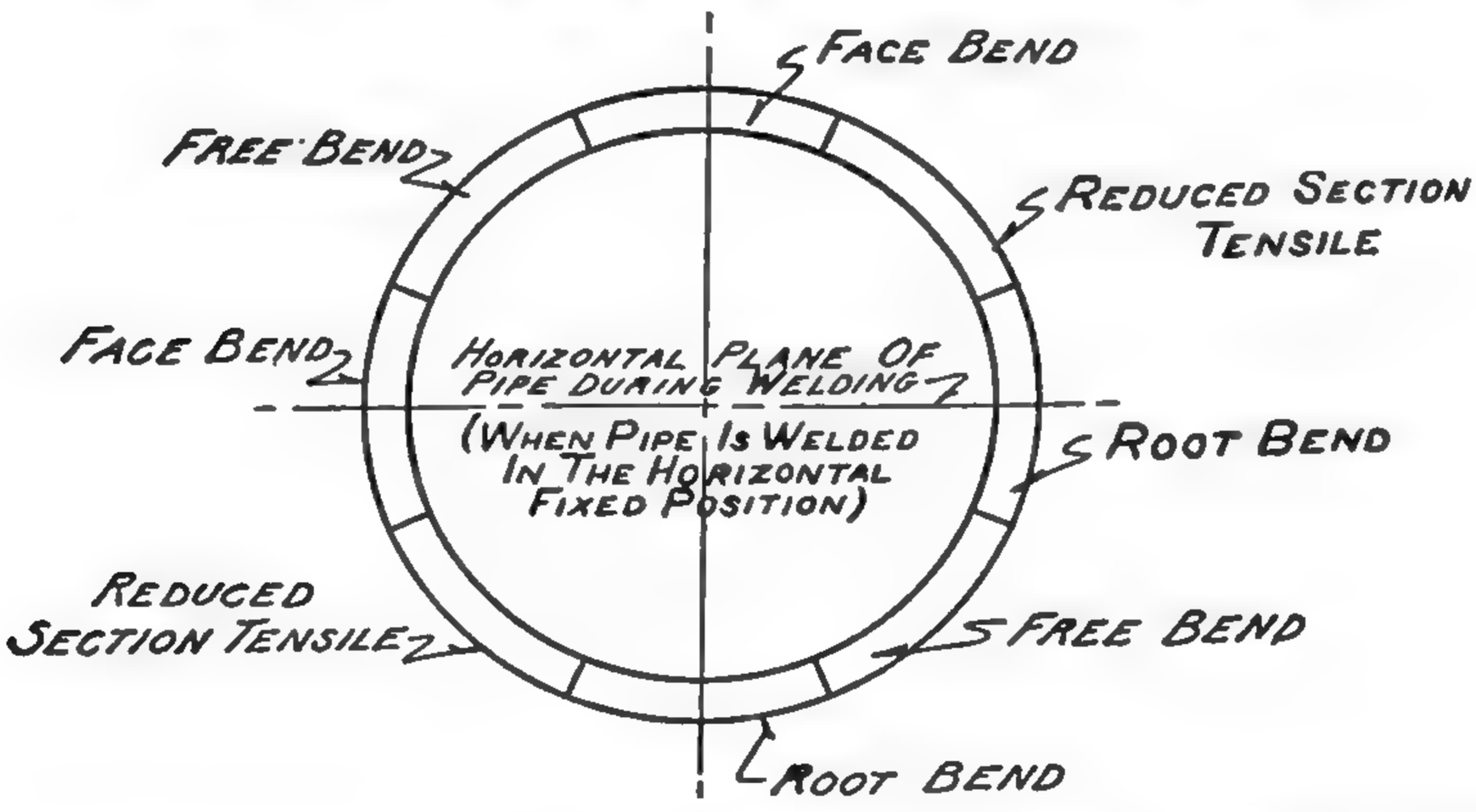


Fig. 15—Order of Removal of Test Specimens from Welded Pipe (for Pipe 3/8 In. Thick)

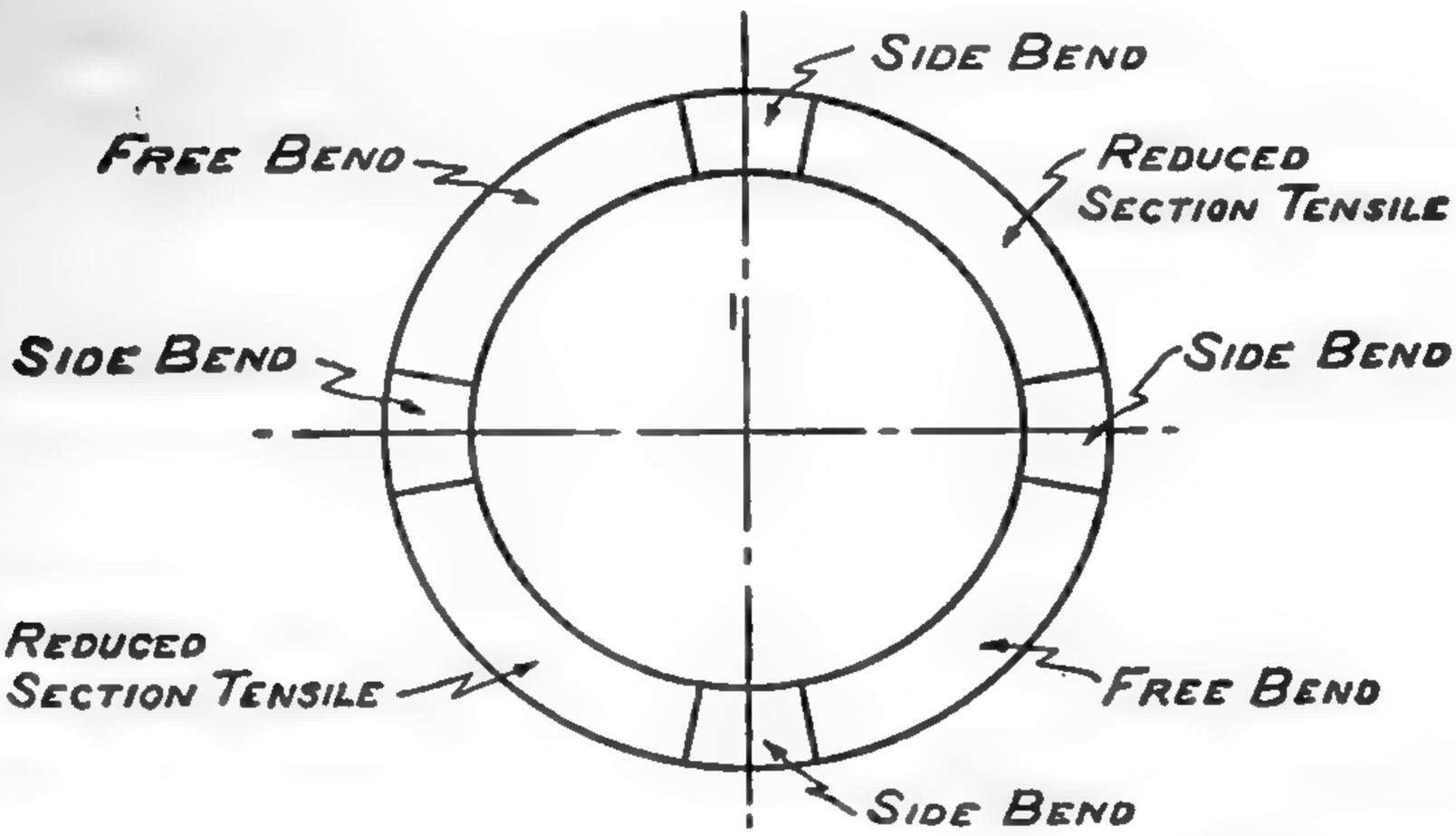
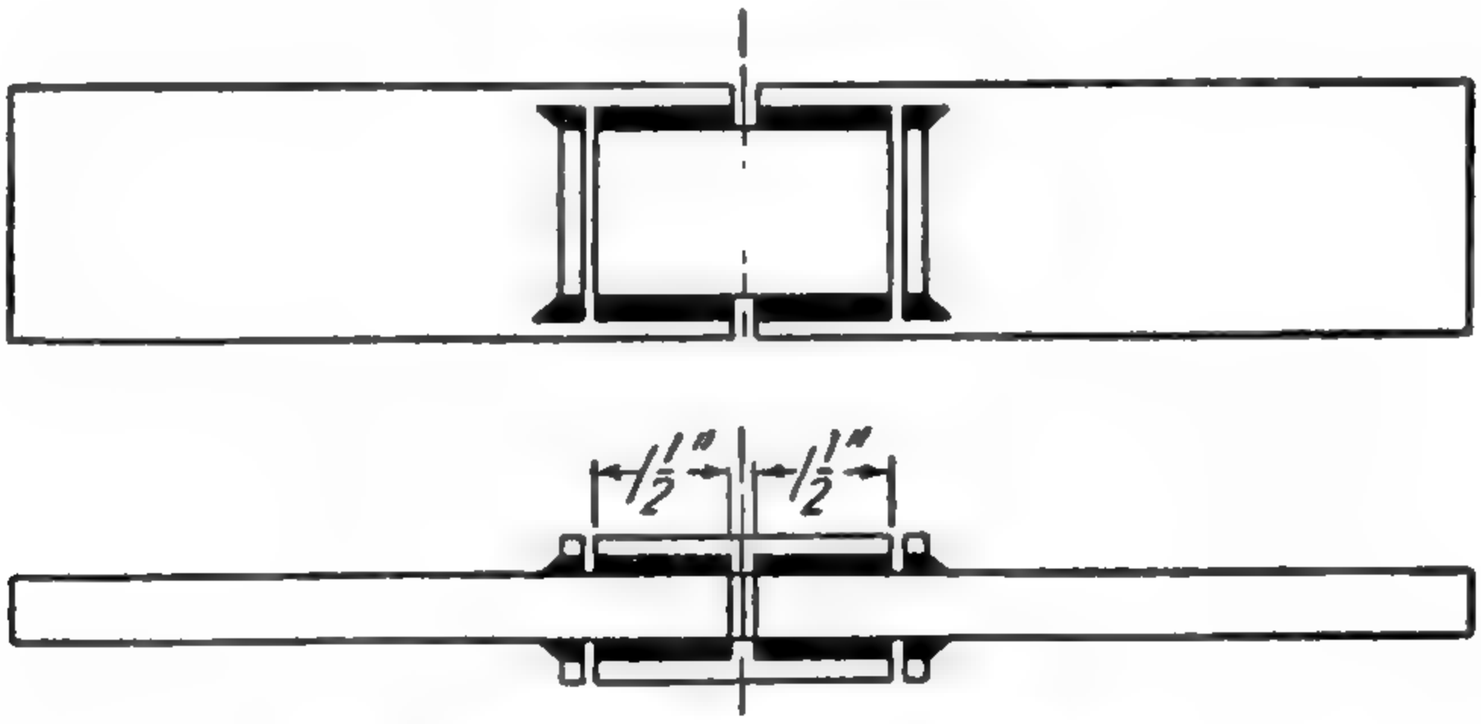
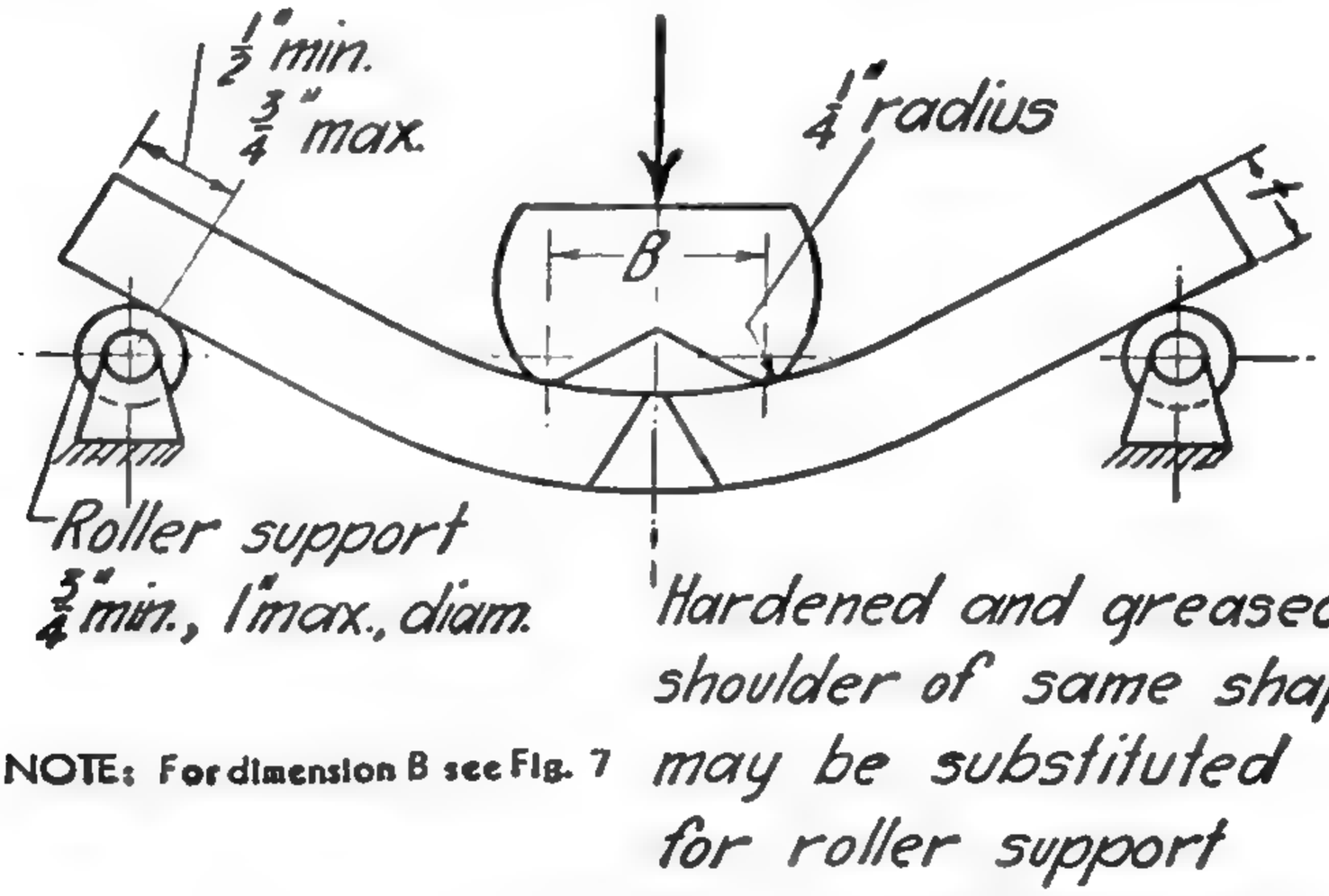


Fig. 16—Order of Removal of Test Specimens from Welded Pipe (for Pipe over ¾ In. Thick)



Note—for other dimensions see Fig. 3

Fig. 17—Longitudinal Fillet-Weld Shearing Specimen After Machining



NOTE: For dimension B see Fig. 7

Fig. 18—Initial Bend for Free-Bend Specimens

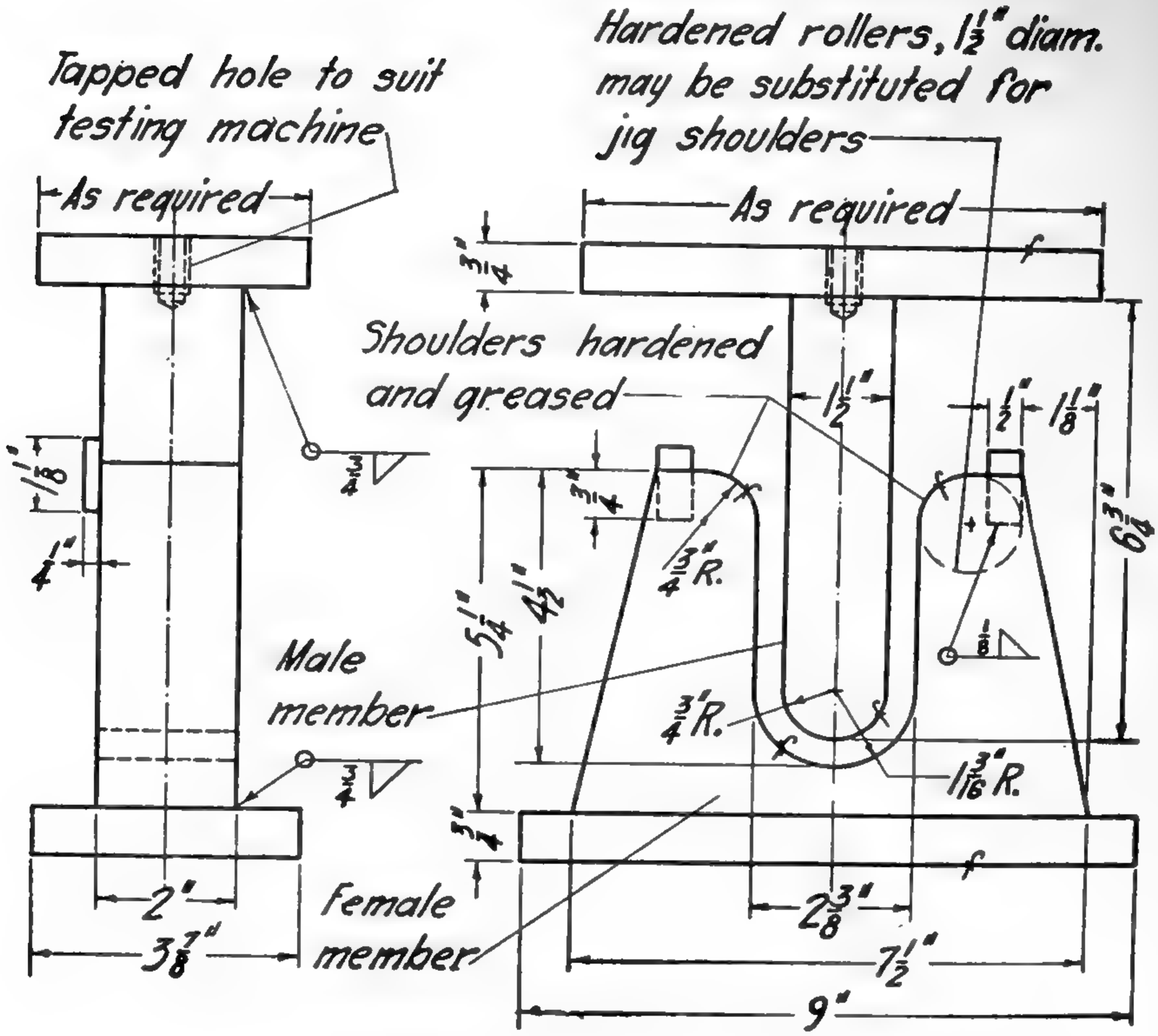


Fig. 19—Guided-Bend Test Jig

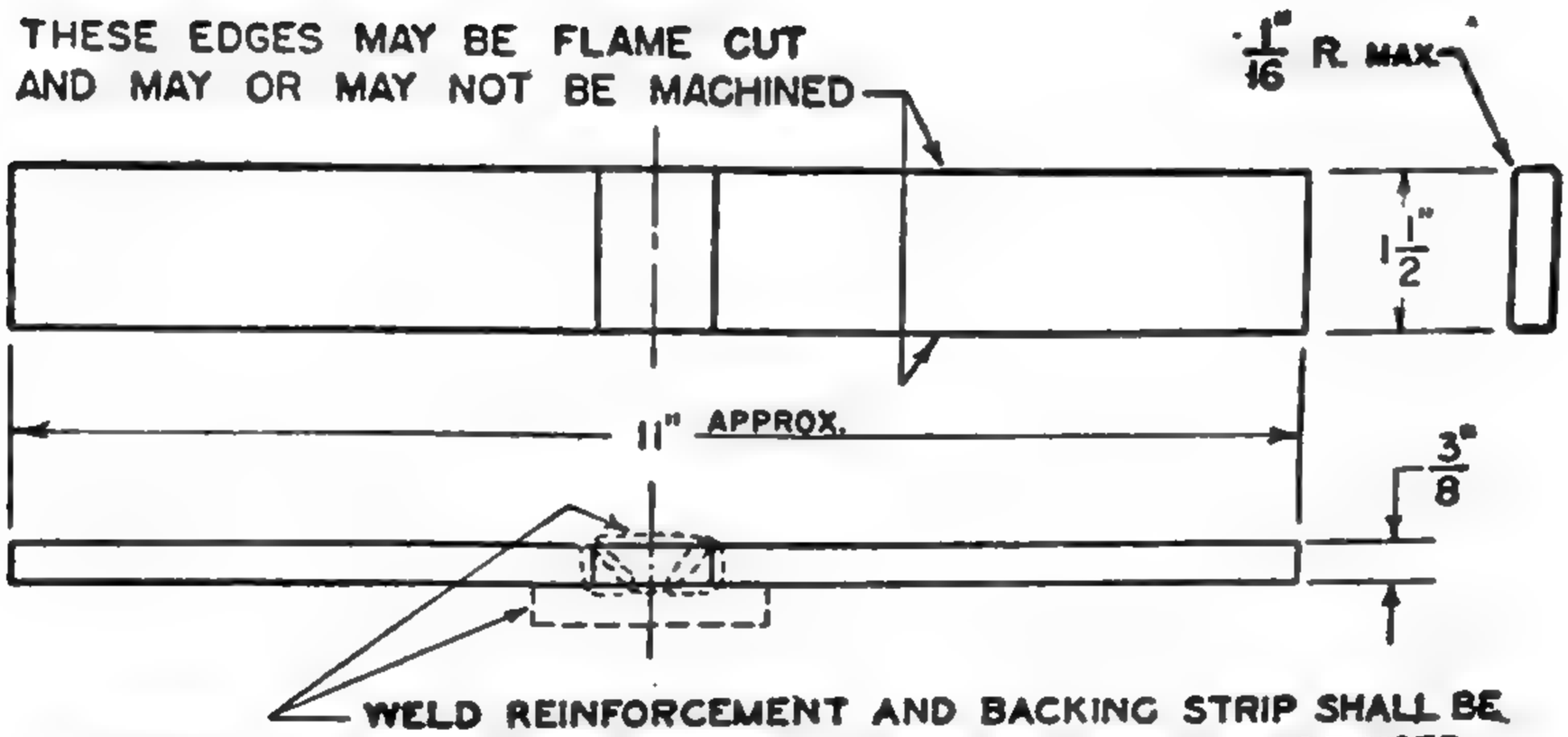
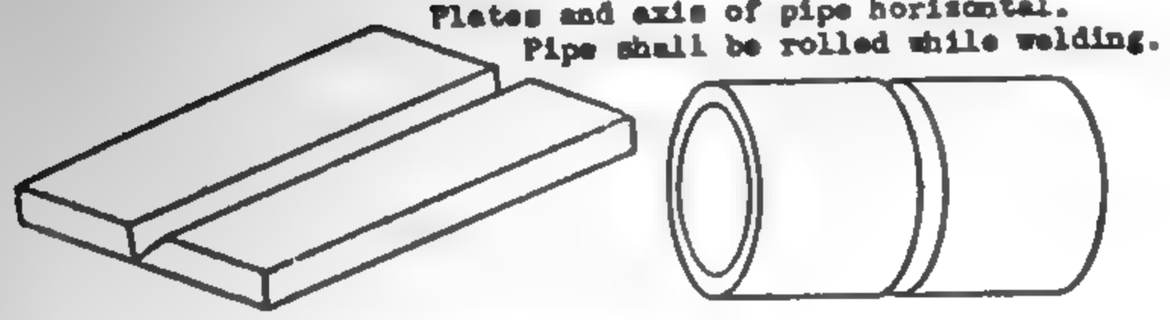
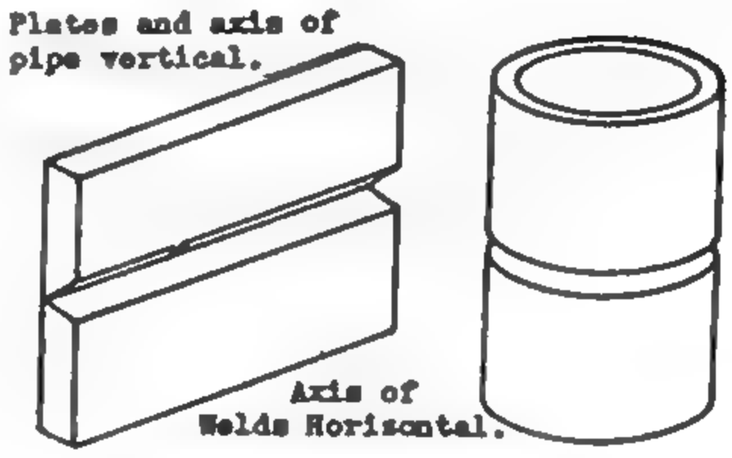


Fig. 20—Fillet-Weld-Soundness Test Specimen

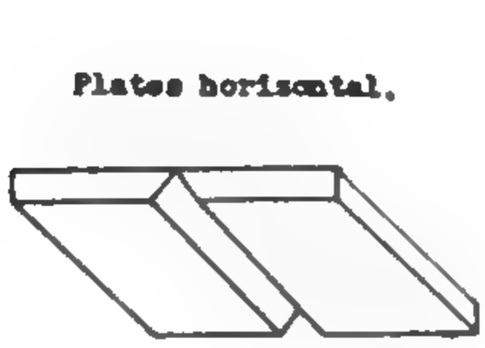


(a) TEST POSITION 1 G

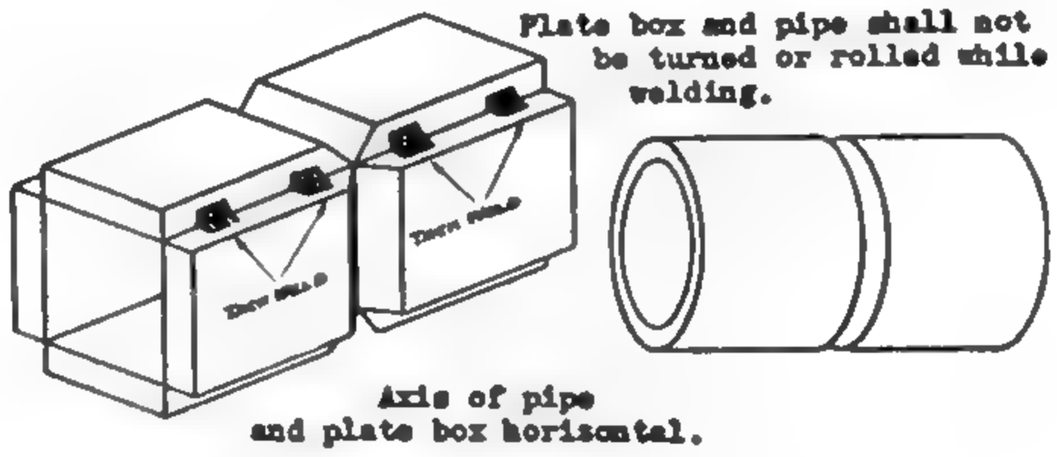


(b) TEST POSITION 2 G

(c) TEST POSITION 3 G



(d) TEST POSITION 4 G



(e) TEST POSITION 5 G

NOTE: For procedure qualification the type of groove shall comply with the Procedure Specification; for operator qualification the shape of the groove and backing strip shall be as shown in Figs. 22, 23 24 and 25.

Fig. 21—Positions of Test Plates or Pipe for Groove Welds

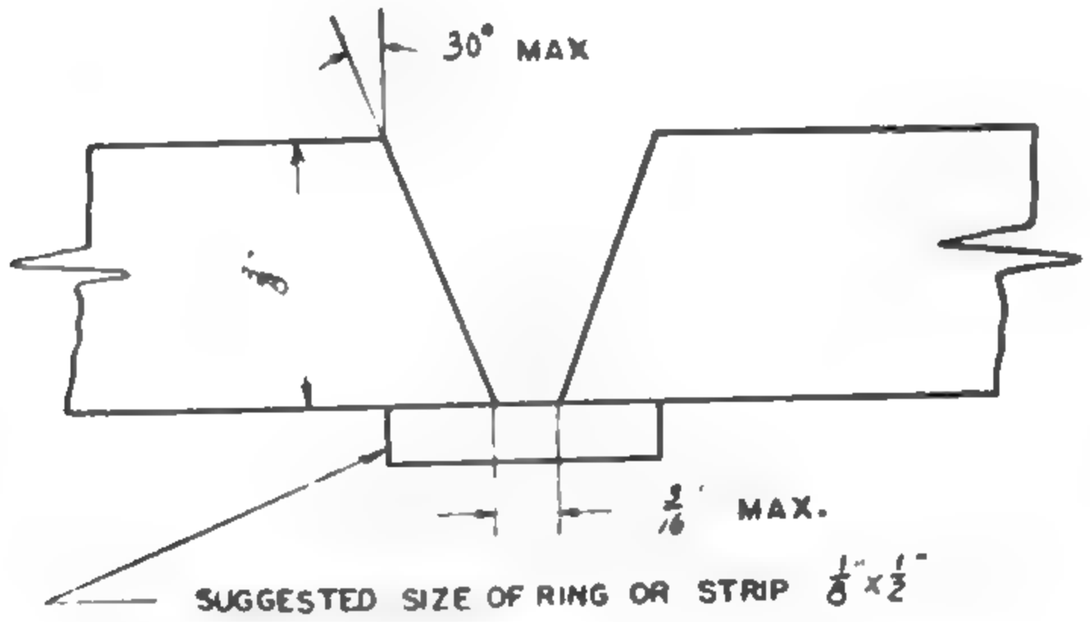


Fig. 22—Butt Joint for Operator Qualification, for Plate or Pipe 3/8 In. Thick

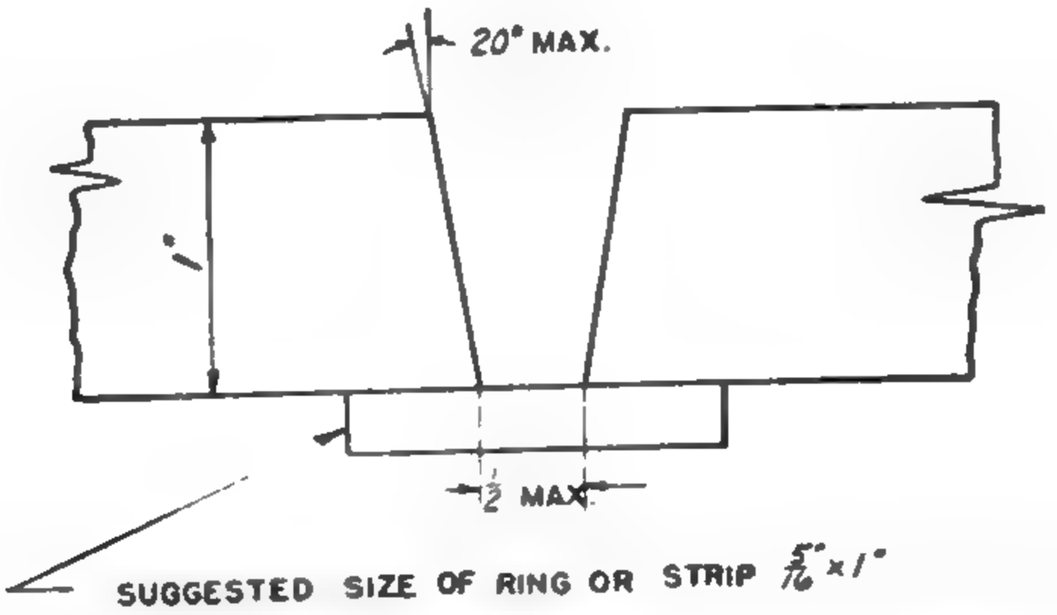


Fig. 23—Butt Joint for Operator Qualification, for Plate or Pipe 1 In. Thick

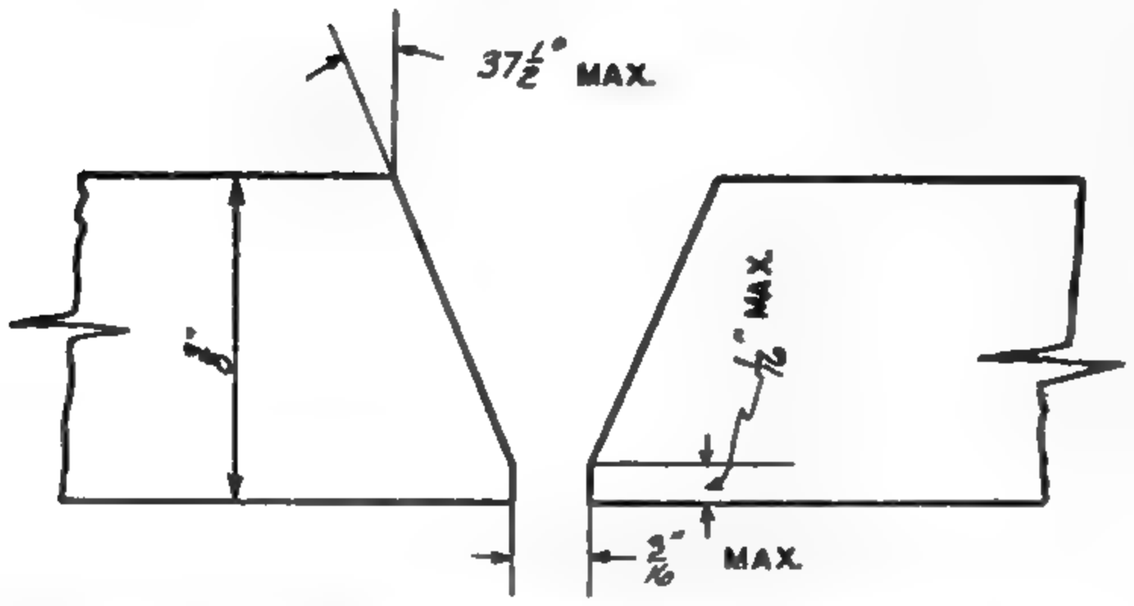


Fig. 24—Alternate Butt Joint for Operator Qualification, for Plate 3/8 In. Thick (May Be Used for the Oxyacetylene Process Only)

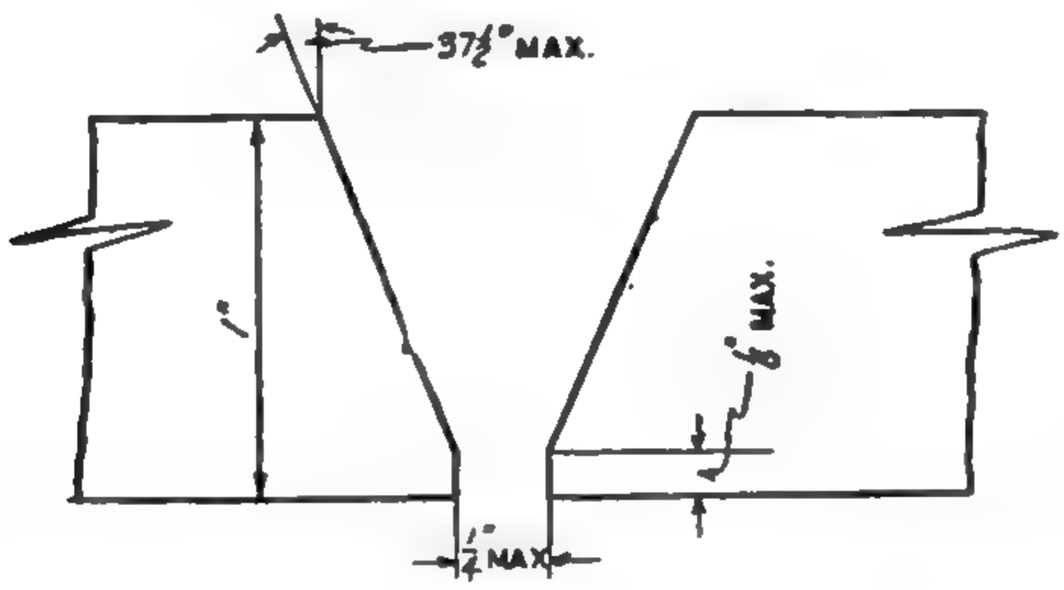
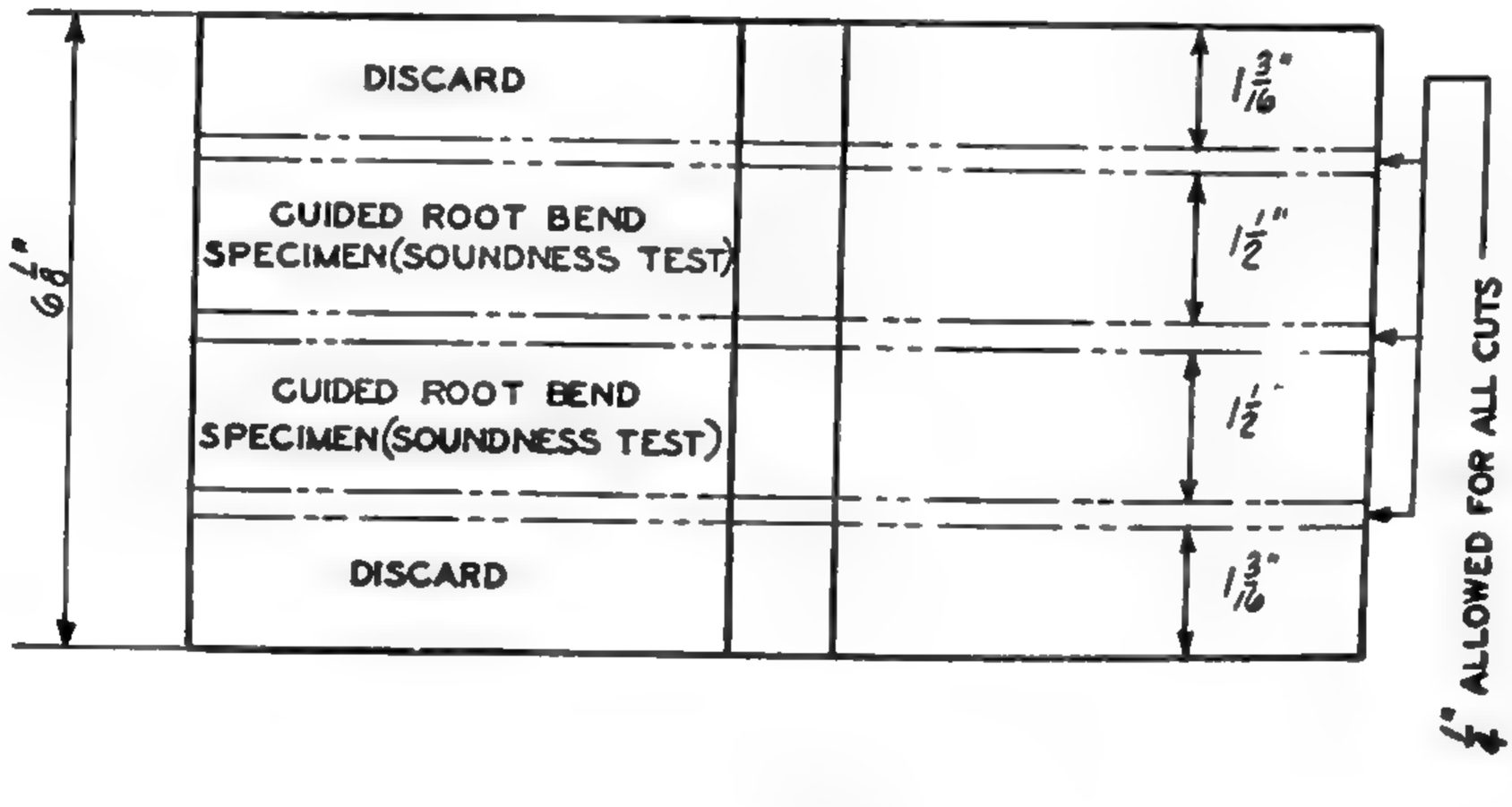


Fig. 25—Alternate Butt Joint for Operator Qualification, for Plate 1 In. Thick (May Be Used for the Oxyacetylene Process Only)



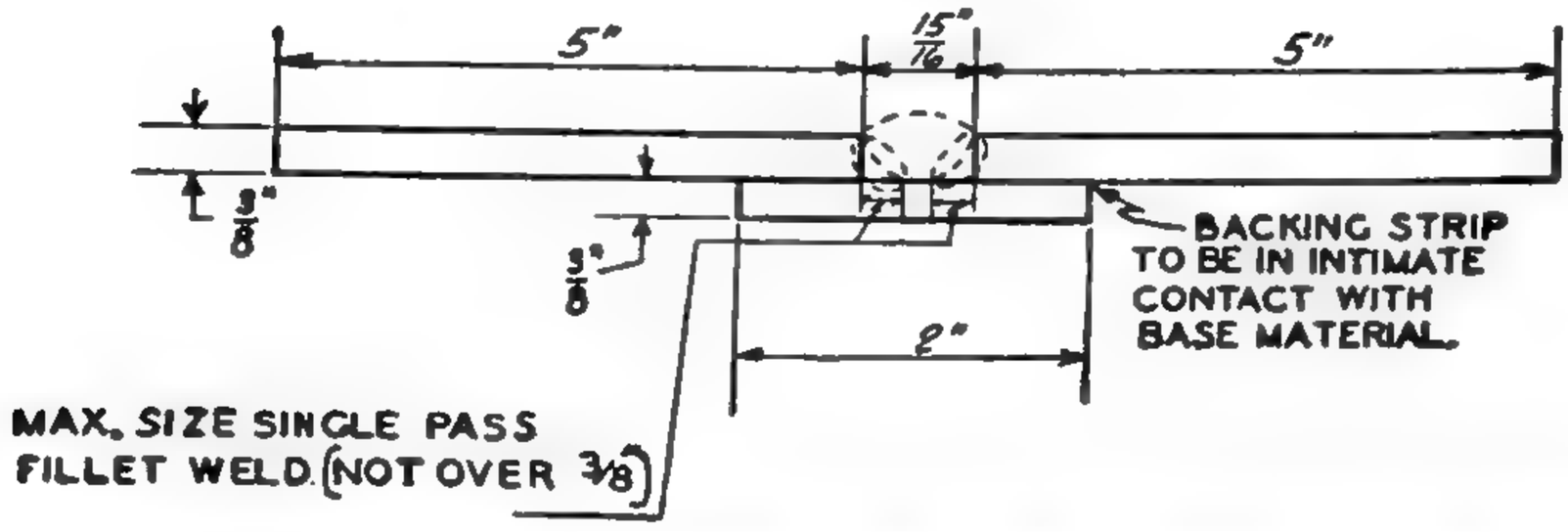
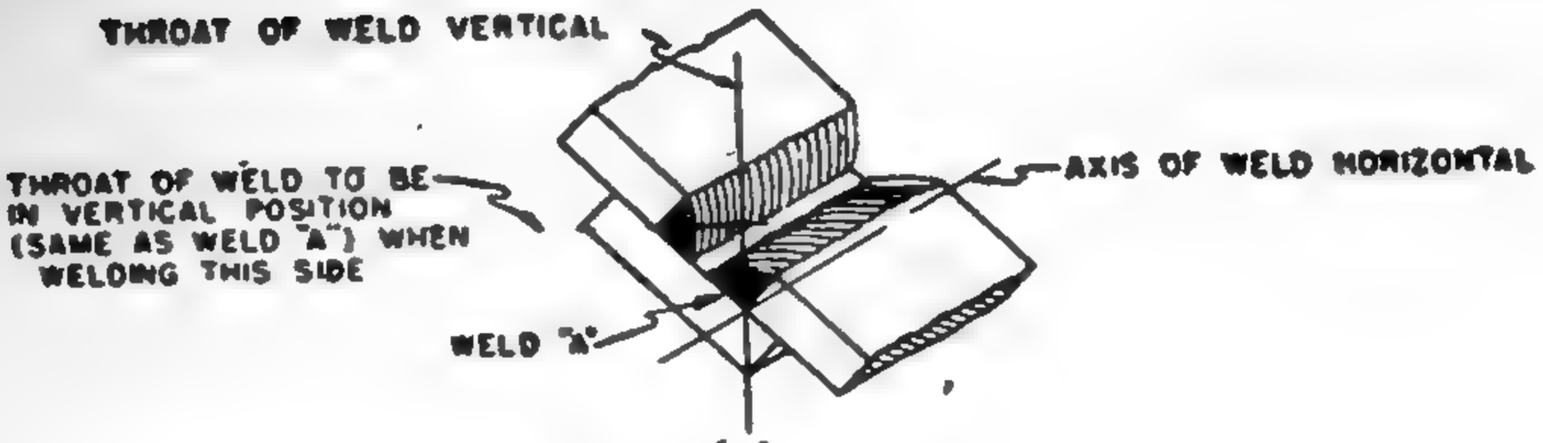
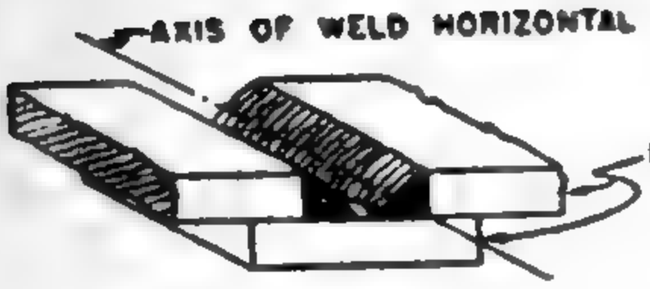
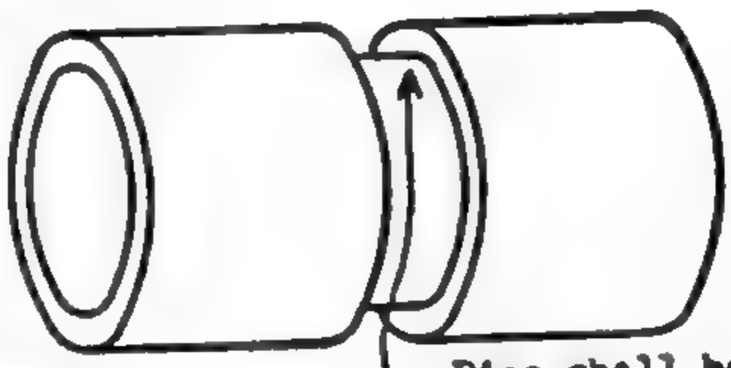


Fig. 26—Test Weld for Soundness Tests (for Operator Qualification Only)

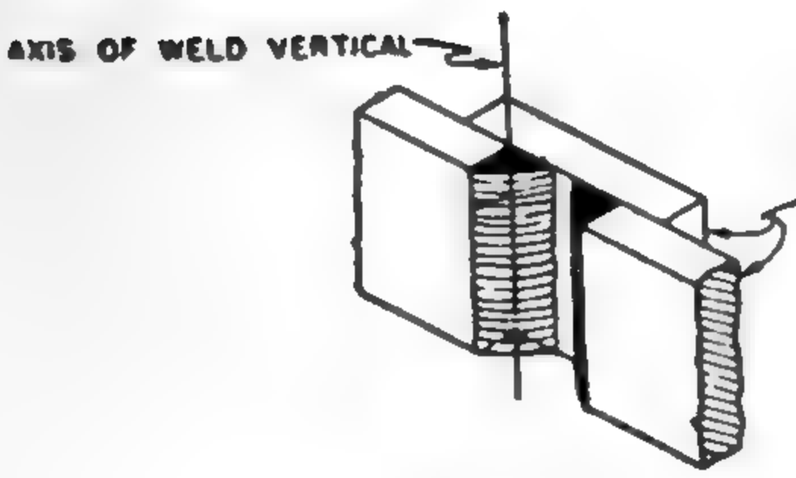


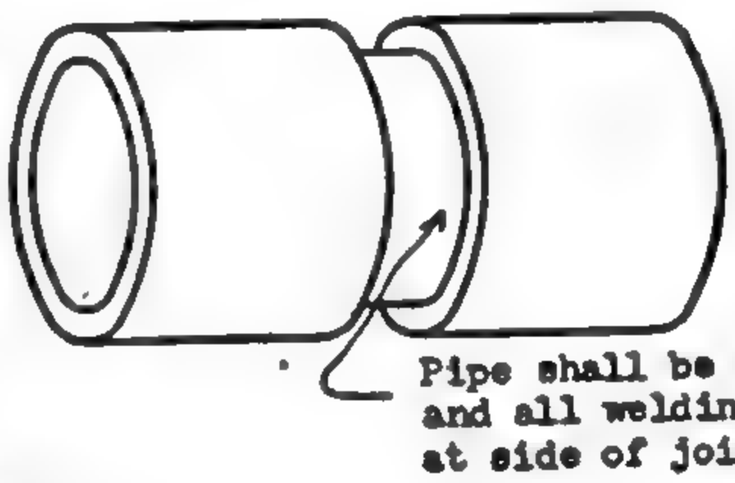
(a)
TEST POSITION 1 F



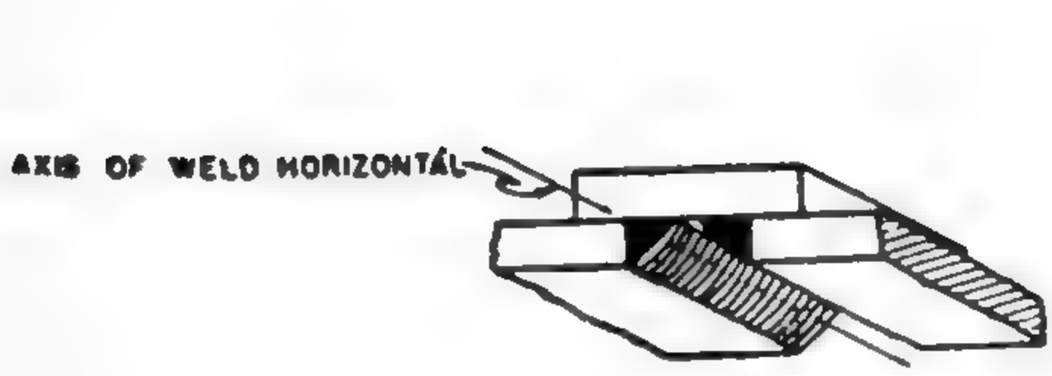


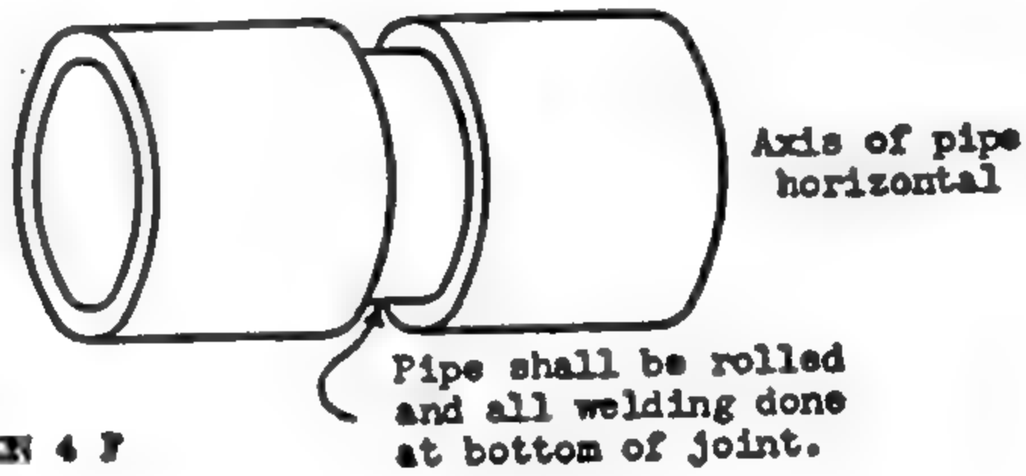
(b)
TEST POSITION 2 F





(c)
TEST POSITION 3 F





(d)
TEST POSITION 4 F

(e)

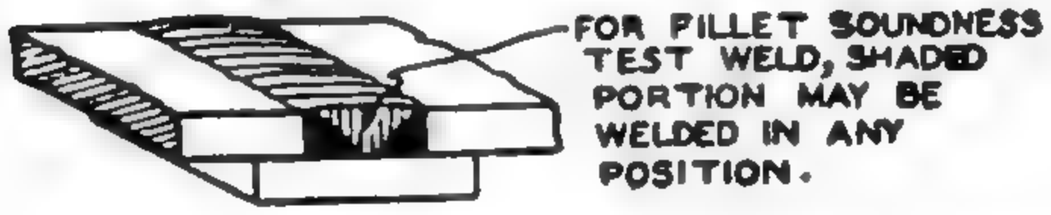


Fig. 27—Positions of Test Plates or Pipe for Fillet Welds (for Operator Qualification Only)

APPENDIX

RECOMMENDED FORMS OF PROCEDURE SPECIFICATIONS

I. Carbcn Arc Welding Process:

PROCEDURE SPECIFICATION FOR CARBON ARC WELDING OF

(State Class of Object to be Welded)

Specification No.....

Date.....

Process: The welding shall be done by the Carbon Arc Process.

Base Metal: The base material shall conform to the Specifications for (insert here references to standard A. S. T. M. or other Code designations, or give the chemical analysis and physical properties).

Filler Metal: The filler metal shall conform to Classification Number —— of the American Welding Society's Specification for (insert here the title of the desired specification).

Position: The welding shall be done in the (give the position or positions in which the welding will be done. See Article 104.)

Preparation of Base Material: The edges or surfaces of the parts to be joined by welding shall be prepared by (state whether sheared, machined, ground, gas cut, etc.), as shown on the attached sketches and shall be cleaned of all oil or grease and excessive amounts of scale or rust, except that a thin coat of linseed oil, if present, need not be removed. (The sketches referred to should show the arrangement of parts to be welded with the spacing and details of the welding groove, if used. Such sketches should be comprehensive and cover the full range of material or base metal thicknesses to be welded.)

Size of Carbon or Graphite Electrodes: The range in size of carbon or graphite electrodes shall be as shown on the attached sketch. (The sketches referred to may be the same as mentioned under "Preparation of Base Material" or may be a separate set. They should show the range of electrode sizes for each thickness of material.)

Nature of Electric Current: The current used shall be (state whether direct or alternating and if alternating give the frequency). The base material shall be on the (state whether negative or positive) side of the line.

Method of Welding: The method of welding used shall be that known as (describe whether "backhand" or "forehand").

Current Characteristics: The approximate voltage and amperage during welding shall be as shown on the attached sketches. (The sketches referred to may be the same as those under "Preparation of Base Material" or under "Number of Layers and Passes of Welding.")

Size of Welding Rod: The size of rod used for the various base material thicknesses shall be as shown on the attached sketches. (The sketches referred to may be the same as mentioned under "Preparation of Base Material" or may be a separate set.)

Number of Layers and Passes of Welding: The number of layers and passes of welding used shall be as shown on the attached sketches. (The sketches referred to may be the same as mentioned under "Preparation of Base Material" or may be a separate set. They should show the range of thicknesses for which one, two or more layers are used.)

Cleaning: All slag or flux remaining on any bead of welding shall be removed before laying down the next successive bead.

Defects Any cracks or blow-holes that appear on the surface of any bead of welding shall be removed by chipping, grinding or gas gouging before depositing the next successive bead of welding.

Peening: (If peening is to be used, it shall be incorporated as part of the Specifications, a description being given of the degree of peening to be done.)

Treatment of Under Side of Welding Groove: (The method of preparing the under or second side of a groove for welding on that side should be stated in this paragraph.)

Preheating: (This paragraph should describe any preheating that will be done.)

Heat Treatment: (This paragraph should describe any heat treatment or stress relieving that is given the welded parts before or after welding.)

Name of Manufacturer

II. Metal Arc Welding Process:

PROCEDURE SPECIFICATION FOR METAL ARC WELDING OF

(State Class of Object to be Welded)

Specification No.....

Date.....

Process: The welding shall be done by the Metal Arc Process.

Base Metal: The base material shall conform to the Specifications for (insert here references to standard A. S. T. M. or other Code designations, or give the chemical analysis and physical properties).

Filler Metal: The filler metal shall conform to Classification Number —— of the American Welding Society's Specification for (insert here the title of the desired specification).

Position: The welding shall be done in the (give the position or positions in which the welding will be done. See Article 104.)

Preparation of Base Material: The edges or surfaces of the parts to be joined by welding shall be prepared by (state whether sheared, machined, ground, gas cut, etc.), as shown on the attached sketches and shall be cleaned of all oil or grease and excessive amounts of scale or rust, except that a thin coat of linseed oil, if present, need not be removed. (The sketches referred to should show the arrangement of parts to be welded with the spacing and details of the welding groove, if used. Such sketches should be comprehensive and cover the full range of material or base metal thicknesses to be welded.)

Nature of Electric Current: The current used shall be (state whether direct or alternating and if alternating give the frequency). The base material shall be on the (state whether negative or positive) side of the line.

Welding Technique: The welding technique, electrode sizes, and mean voltages and currents for each electrode shall be substantially as shown on the attached sketches. (The sketches referred to may be the same as mentioned under "Preparation of Base Material" or may be separate sketches. They should show for the minimum thickness and for several intermediate thicknesses of base material, the welding technique to be used, whether weaving or beading, the number of layers or passes and diameter of electrode with the mean voltage and current for each layer or pass, and in the case of vertical welds, the progression of each pass, whether upward or downward.)

NOTE: Since, in the welding of many materials in the flat position and particularly for the ordinary mild steels, the proper welding "heat" can be readily determined by the appearance of the individual beads of welding, the use of a "Standard Appearance Weld" may be desirable for the flat position. Such a weld should be made in the maximum thickness that will be used in construction, except that the maximum thickness of the Standard Appearance Weld need not exceed ¾ in., and should show approximately 2 in. of the surface of each layer and a cross section through the weld at each layer, where such cross section is found necessary to produce a clearly understandable photograph. When a Standard Appearance Weld is used the following paragraph should be used in lieu of specifying current and voltage values.

Appearance of Welding Layers: The welding current and manner of depositing the weld metal shall be such that the layers of welding as deposited shall have the appearance shown on the photographs attached hereto. There shall be practically no undercutting on the side walls of the welding groove or the adjoining base material.

Cleaning: All slag or flux remaining on any bead of welding shall be removed before laying down the next successive bead.

Defects: Any cracks or blow-holes that appear on the surface of any bead of welding shall be removed by chipping, grinding or gas gouging before depositing the next successive bead of welding.

Peening: (If peening is to be used, it shall be incorporated as part of the Specifications, a description being given of the degree of peening to be done.)

Treatment of Under Side of Welding Groove: (The method of preparing the under or second side of a groove for welding on that side should be stated in this paragraph.)

Preheating: (This paragraph should describe any preheating that will be done.)

Heat Treatment: (This paragraph should describe any heat treatment or stress relieving that is given the welded parts before or after welding.)

Name of Manufacturer

III. Oxyacetylene Welding Process:

PROCEDURE SPECIFICATION FOR OXYACETYLENE WELDING OF

(State Class of Objects to be Welded)

Specification No.....

Date.....

Process: The welding shall be done by the Oxyacetylene Process.

Base Metal: The base material shall conform to the Specifications for (insert here references to standard A. S. T. M. or other Code designations, or give the chemical analysis and physical properties).

Filler Metal: The filler metal shall conform to Classification Number —— of the American Welding Society's Specification for (insert here the title of the desired specification).

Position: The welding shall be done in the (give the position or positions in which the welding will be done. See Article 104.)

Preparation of Base Material: The edges or surfaces of the parts to be joined by welding shall be prepared by (state whether sheared, machined, ground, gas cut, etc.), as shown on the attached sketches and shall be cleaned of all oil or grease and excessive amounts of scale or rust, except that a thin coat of linseed oil, if present, need not be removed. (The sketches referred to should show the arrangement of parts to be welded with the spacing and details of the welding groove, if used. Such sketches should be comprehensive and cover the full range of material or base metal thicknesses to be welded.)

Size of Welding Tip: The range in size of welding tips used shall be as shown on the attached sketch. (The sketches referred to may be the same as mentioned under "Preparation of Base Material" or may be a separate set. They should show the range of tip sizes for each thickness of material.)

Nature of Flame: The flame used for welding shall be (state whether a neutral flame or one with slight excess of acetylene is to be used).

Method of Welding: The method of welding used shall be that known as (describe whether "backhand" or "forehand").

Size of Welding Rod: The size of rod used for the various base material thicknesses shall be as shown on the attached sketch. (The sketches referred to may be the same as mentioned under "Preparation of Base Material" or may be a separate set.)

Number of Layers of Welding: The number of layers of welding used shall be as shown on the attached sketches. (The sketches referred to may be the same as mentioned under "Preparation of Base Material" or may be a separate set. They should show the range of thicknesses for which one, two or more layers are used.)

Cleaning: All slag or flux remaining on any layer of welding shall be removed before laying down the next successive layer.

Defects: Any cracks or blow-holes that appear on the surface of any layer of welding shall be removed by chipping, grinding, or gas gouging before depositing the next successive bead of welding.

Peening: (If peening is to be used, it shall be incorporated as part of the Specifications, a description being given of the degree of peening to be done.)

Treatment of Under Side of Welding Groove: (The method of preparing the under or second side of a groove for welding on that side should be stated in this paragraph.)

Preheating: (This paragraph should describe any preheating that will be done.)

Heat Treatment: (This paragraph should describe any heat treatment or stress relieving that is given the welded parts before or after welding.)

Name of Manufacturer

CHAPTER 61

FILLER METAL SPECIFICATIONS*

A. Tentative Specifications for

AMERICAN WELDING SOCIETY
SPECIFICATION A 5.1-48T

MILD STEEL ARC-WELDING ELECTRODES[1]

A.S.T.M. Designation: A 233 – 48 T

ISSUED, 1940; REVISED, 1942, 1943, 1945, 1948.[2]

These Tentative Specifications have been approved by the sponsoring committee and accepted by the Cooperating Societies in accordance with established procedures, for use pending adoption as standard. Suggestions for revisions should be addressed to the Headquarters of the A.S.T.M., 1916 Race St.. Philadelphia 3, Pa., or of the A.W.S., 33 W. 39th St., New York 18, N. Y.

These specifications were prepared jointly by the American Welding Society and the American Society for Testing Materials.

Scope

1. These specifications cover light-coated and covered metal arc-welding electrodes for the welding of carbon and low-alloy steels of weldable quality.

PART I.—CLASSIFICATION AND ACCEPTANCE

Classification

2. (*a*) The electrodes are classified in Table I on the basis of the tensile strength of the deposited weld metal, type of covering, and type of current and welding positions of the electrodes.

(*b*) Any electrode classified under one classification shall not be classified under any other classification.

Manufacture

3. The electrodes may be made by any methods that will yield a product conforming to the requirements of these specifications.

Chemical Composition

4. The electrodes shall not be required to comply with any limitations on the chemistry of electrode or of deposited metal.

Physical Tests

5. (*a*) Physical tests, comprising (*1*) an all-weld-metal tension test to determine the mechanical properties of the deposited metal, and (*2*) guided-bend and fillet-weld tests to demonstrate the usability of an electrode as to welding position, soundness of weld metal and of fusion zone and weld contour, shall be performed at the place of manufacture of the electrodes, for the purpose of

[1] Under the standardization procedure of the two Societies, these specifications are under the jurisdiction of the A.W.S.-A.S.T.M. Joint Committee on Filler Metal.

[2] Latest revision accepted by the A.S.T.M. Administrative Committee on Standards, June 7, 1948; approved by A.W.S. Board of Directors, May 17, 1948.

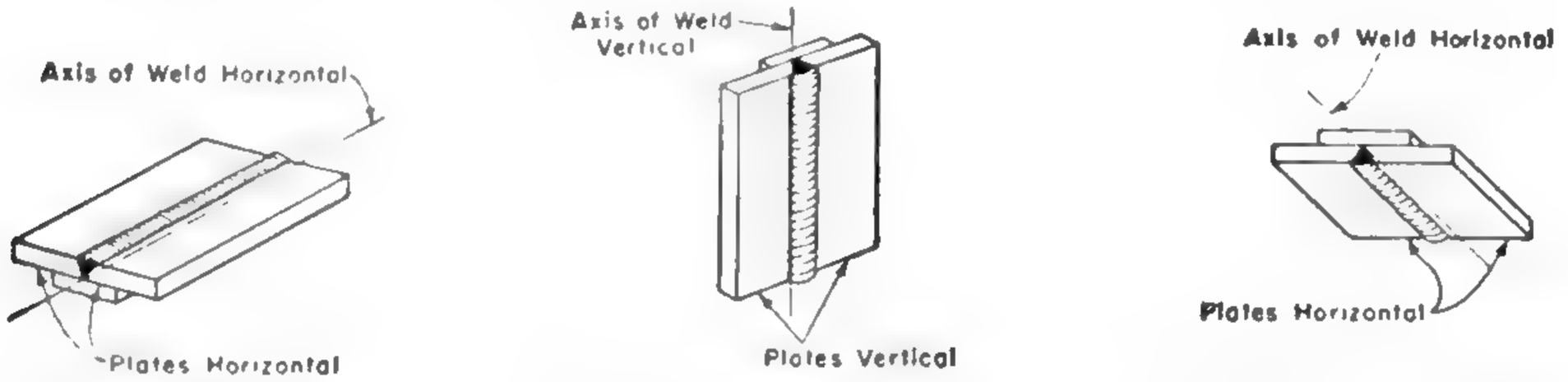
These specifications, together with the Tentative Specifications for Low-Alloy Steel Arc-Welding Electrodes (A 316 - 48 T), represent a revision of the former Tentative Specifications for Iron and Steel Arc-Welding Electrodes (A 233 - 45 T). Prior to 1940, Specifications A 233 comprised a portion of the former Tentative Specifications for Iron and Steel Filler Metal (Arc-Welding Electrodes and Gas-Welding Rods) (A 205 - 37 T).

* Prepared by the AWS-ASTM Committee on Filler Metal

TABLE I.—ELECTRODE CLASSIFICATION.

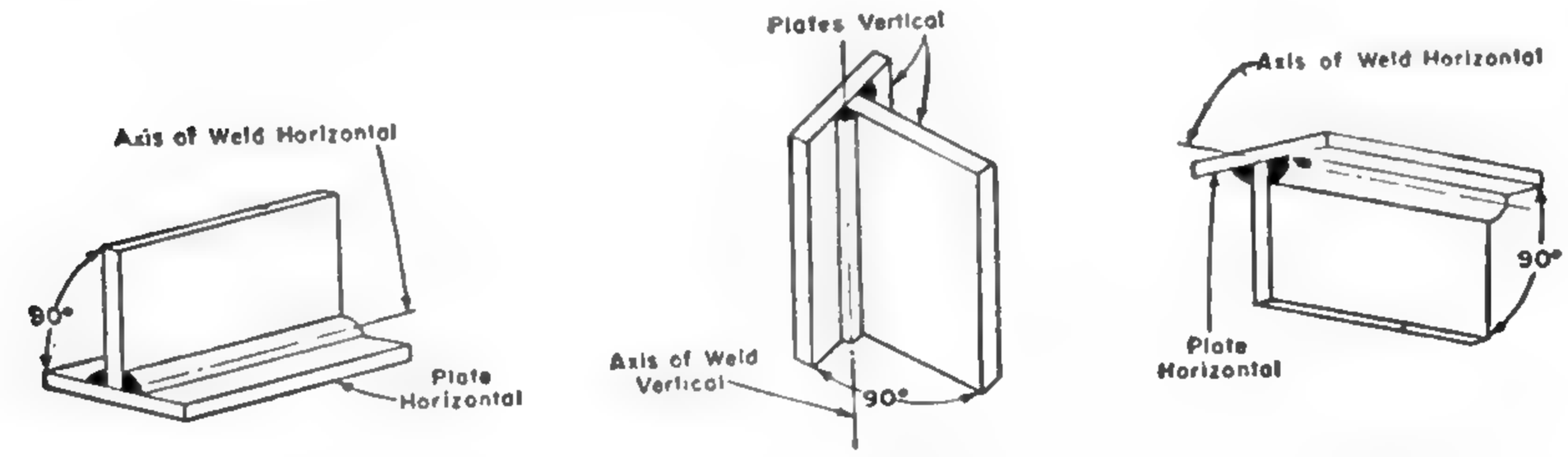
Electrode Classification Number	Type of Coating or Covering	Capable of Producing Satisfactory Welds in Positions Shown[a]	Type of Current
E45 SERIES.—MINIMUM TENSILE STRENGTH OF DEPOSITED METAL IN NON-STRESS-RELIEVED CONDITION 45,000 PSI.			
E4510.....	Sulcoated or light coated	F, V, OH, H	Not specified, but generally d.c., straight polarity (electrode negative).
E4520.....	Sulcoated or light coated	H-Fillets, F	Not specified, but generally d.c., straight polarity (electrode negative).
E60 SERIES.—MINIMUM TENSILE STRENGTH OF DEPOSITED METAL IN NON-STRESS-RELIEVED CONDITION 62,000 PSI. (OR HIGHER—SEE TABLE II).			
E6010.....	High cellulose sodium	F, V, OH, H	For use with d.c., reversed polarity (electrode positive) only.
E6011.....	High cellulose potassium	F, V, OH, H	For use with a.c. or d.c., reversed polarity (electrode positive).
E6012.....	High titania sodium	F, V, OH, H	For use with d.c., straight polarity (electrode negative), or a.c.
E6013.....	High titania potassium	F, V, OH, H	For use with a.c. or d.c., straight polarity (electrode negative).
E6015.....	Low hydrogen sodium	F, V, OH, H	For use with d.c., reversed polarity (electrode positive) only.
E6016.....	Low hydrogen potassium	F, V, OH, H	For use with a.c. or d.c., reversed polarity (electrode positive).
E6020.....	High iron oxide	H-Fillets, F	For use with d.c., straight polarity (electrode negative), or a.c. for horizontal fillet welds; and d.c., either polarity, or a.c., for flat-position welding.
E6030.....	High iron oxide	F	For use with d.c., either polarity, or a.c.

[a] The abbreviations F, H, V, OH, and H-Fillets indicate welding positions (Figs. 1 and 2) as follows:
F = Flat
H = Horizontal
H-Fillets = Horizontal Fillets
V = Vertical } For electrodes 5/16 in. and under except in classifications E6015 and E6016, 5/32 in. and under.
OH = Overhead }



(a) Flat Groove Welds. (b) Vertical Groove Welds (c) Overhead Groove Welds.

FIG. 1—Positions of Test Plates for Welding Guided-Bend Test Specimens.



(a) Horizontal Fillet Welds. (b) Vertical Fillet Welds. (c) Overhead Fillet Welds.

FIG. 2.—Positions of Test Plates for Welding Fillet-Weld Test Specimens.

classification, when and as prescribed by the electrode manufacturer.

(*b*) At the option and expense of the purchaser any or all of the tests prescribed in Paragraph (*a*) may be used as a basis for acceptance of electrodes. The guided-bend test, or fillet-weld test, or both, are usually sufficient to determine acceptability.

Methods of Test

6. Test specimens shall be prepared in kind and in number as specified in Table II and tests shall be conducted in accordance with Sections 17 to 22 of these specifications.

Test Requirements

7. In order to be classified under these specifications an electrode shall be capable of yielding the following results:

(*a*) The all-weld-metal tension test specimens shall conform to the requirements prescribed in Table III.

(*b*) Guided-bend test specimens, after bending, shall show no crack or other open defect exceeding $\frac{1}{8}$ in. measured in any direction. Cracks occurring on corners of a specimen during testing shall not be considered.

(*c*) The fillet-weld test specimen shall upon examination be free from cracks or other open defects affecting its strength. Upon examination of the face that has been polished and etched as prescribed, it is required that:

(*1*) Each fillet weld shall have penetrated to or beyond the junction of the plate edges,

(*2*) Both legs of each fillet weld shall be of equal length within $\frac{1}{16}$ in.,

(*3*) The convexity (of convex fillet welds) shall be not more than $\frac{3}{64}$ in. for a $\frac{1}{8}$-in. fillet weld, plus $\frac{1}{64}$ in. additional for each additional $\frac{1}{8}$ in. of fillet weld size (see Fig. 10),

(*4*) The welds and the base metal shall be free from cracks, and

(*5*) The weld shall be reasonably free from undercutting, overlap, trapped slag and porosity.

(*d*) The amount of gas collected in the determination for hydrogen as specified in Section 22, shall not exceed an average of 0.1 cu. cm. per gram of deposited metal for the four specimens tested.

Retests

8. If any specimen fails, one additional test assembly shall be welded and tested in accordance with the requirements of Section 7.

Insulation

9. The coverings shall have sufficient electrical resistance to effectively insulate against a difference of potential of 100 v., 60 cycles a.c.

NOTE.—This does not apply to coiled wire which is to be used for machine welding or to electrodes of the E45 series of classification.

Core Wire and Coverings

10. (*a*) The diameter of the core wire shall not vary more than plus or minus 0.002 in. from the standard size specified. The length shall not vary more than plus or minus $\frac{1}{4}$ in. from that specified.

(*b*) The covering on covered electrodes of all sizes shall be concentric to the extent that the maximum core-plus-one-covering dimension shall not exceed the minimum core-plus-one-covering dimension by more than 3 per cent. The concentricity shall be measured by any suitable means.

(*c*) Core wire and coverings shall be free of defects which would interfere with uniform performance of the electrodes.

Exposed Core

11. (*a*) Covered electrodes for manual welding shall be bare or free from covering for a distance of about $\frac{3}{4}$ in., but not more than $1\frac{1}{4}$ in., for making contact with the holder.

(*b*) The arc end of each electrode shall be sufficiently bare to permit easy striking of the arc. The distance from the arc end to the first point where the full cross-section of the covering prevails shall not exceed the diameter of the core wire. However, for electrodes larger than $\frac{1}{8}$ in. the core wire shall not be

TABLE II.—SUMMARY OF TESTS REQUIRED.[a]

Classification Number	Electrode		All-Weld Metal Tension Test[b]	Guided-Bend Test[c]	Fillet-Weld Test[d]	Hydrogen Test[e]
	Diameter, in.	Current and Polarity				
E4510	1/16 to 1/8, incl.	not specified	not required	not required	not required	not required
	5/32 and 3/16		F	not required	not required	not required
	7/32 and 1/4		not required	not required	not required	not required
	5/16		not required	not required	not required	not required
E4520	1/16 to 1/8, incl.	not specified	not required	not required	not required	not required
	5/32 and 3/16		F	not required	not required	not required
	7/32 and 1/4		not required	not required	not required	not required
	5/16		not required	not required	not required	not required
E6010	1/16 to 1/8, incl.	d.c., reversed polarity (electrode positive)	not required	not required	not required	not required
	5/32 and 3/16		F	V and OH	V and OH	not required
	7/32		not required	not required	not required	not required
	1/4		F	F	H	not required
	5/16		F	F	not required	not required
E6011	1/16 to 1/8, incl.	a.c. and d.c., reversed polarity (electrode positive)	not required	not required	not required	not required
	5/32 and 3/16		F	V and OH	V and OH	not required
	7/32		not required	not required	not required	not required
	1/4		F	F	H	not required
	5/16		F	F	not required	not required
E6012	1/16 to 1/8, incl.	d.c., straight polarity (electrode negative), and a.c.	not required	not required	not required	not required
	5/32 and 3/16		F	V and OH	V and OH	not required
	7/32		not required	not required	not required	not required
	1/4		F	F	H	not required
	5/16		F	F	not required	not required
E6013	1/16 to 1/8, incl.	a.c. and d.c., straight polarity (electrode negative)	not required	not required	not required	not required
	5/32 and 3/16		F	V and OH	V and OH	not required
	7/32		not required	not required	not required	not required
	1/4		F	F	H	not required
	5/16		F	F	not required	not required
E6015	1/16 to 1/8, incl.	d.c., reversed polarity (electrode positive)	not required	not required	not required	not required
	5/32		F	V and OH	V and OH	not required
	3/16		F	F	H	F
	7/32		not required	not required	not required	not required
	1/4		F	F	H	not required
	5/16		F	F	not required	not required
E6016	1/16 to 1/8, incl.	a.c. and d.c., reversed polarity (electrode positive)	not required	not required	not required	not required
	5/32		F	V and OH	V and OH	not required
	3/16		F	F	H	F
	7/32		not required	not required	not required	not required
	1/4		F	F	H	not required
	5/16		F	F	not required	not required
E6020	1/16 to 1/8, incl.	d.c., straight polarity (electrode negative), and a.c. for horizontal fillet welds; d.c., both polarities, and a.c., for flat-position welding	not required	not required	not required	not required
	5/32 and 3/16		F	F	H	not required
	7/32		not required	not required	not required	not required
	1/4		F	F	H	not required
	5/16		F	F	not required	not required
E6030	1/16 to 1/8, incl.	d.c., both polarities, and a.c.	not required	not required	not required	not required
	5/32 and 3/16		F	F	not required	not required
	7/32		not required	not required	not required	not required
	1/4		F	F	not required	not required
	5/16		F	F	not required	not required

[a] For electrodes smaller than 5/32 in. and for the 7/32-in. size, the specified tests would require detailed modification; such sizes may be judged from the results of tests on the 5/32- and 1/4-in. sizes, respectively.
[b] See Sections 7 and 19.
[c] See Sections 7 and 20.
[d] See Sections 7 and 21.
[e] See Sections 7 and 22.

exposed around more than one-half the circumference at a distance of $\frac{1}{8}$ in. or more from the arc end.

Standard Sizes and Lengths

12. Standard sizes and lengths of electrodes are as shown in the following table. In all cases, standard size refers to the diameter of the core wire.

Standard Sizes, Diameter of Core Wire, in.	Standard Lengths, in.[a]
$\frac{1}{16}$	9 or 18[b]
$\frac{5}{64}$ and $\frac{3}{32}$	12 or 18[b]
$\frac{1}{8}$ and $\frac{5}{32}$	14
$\frac{3}{16}$	14 or 18
$\frac{7}{32}$, $\frac{1}{4}$, $\frac{5}{16}$ and $\frac{3}{8}$	18

[a] Electrodes may also be provided in coils or reels.
[b] In the case of 18-in. lengths of $\frac{1}{16}$, $\frac{5}{64}$ and $\frac{3}{32}$-in. electrodes, center-gripping of the electrodes is standard. In all other cases, end gripping is standard.

TABLE III.—MINIMUM TENSILE STRENGTH AND DUCTILITY REQUIREMENTS FOR ALL-WELD-METAL TENSION TEST IN THE AS-WELDED CONDITION.[a]

Electrode Classification Number	Tensile Strength, min., psi.	Yield Point, min., psi.	Elongation in 2. in., min., per cent
E4510	45 000	not specified	5
E4520	45 000	not specified	5
E6010	62 000	52 000	22
F6011	62 000	52 000	22
E6012	68 000	55 000	17
E6013	68 000	55 000	17
E6015	68 000	55 000	22
E6016	68 000	55 000	22
E6020	62 000	52 000	25
E6030	62 000	52 000	25

[a] See Table II for sizes to be tested.

Packaging

13. Electrodes shall be packaged as follows:

(*a*) Bundles or boxes, not exceeding 50 lb. net weight, or

(*b*) Coils or reels, not exceeding approximately 200 lb. net weight.

Marking

14. All bundles, boxes, coils, or reels shall be legibly marked with the following information:

(*a*) Classification,

(*b*) Manufacturer's name and trade designation,

(*c*) Size and net weight, and

(*d*) Guarantee.

Color Markings for Electrode Identification

15. All electrodes shall be color marked in accordance with the current "Standard for Color Markings for Electrode Identification" of the National Electrical Manufacturers Association.

Guarantee

16. The manufacturer shall guarantee that the electrodes in all sizes and classifications conform to these specifications and each container shall be so marked. The manufacturer's responsibility shall be limited to replacement of any electrodes which do not conform to the requirements of these specifications.

Part II.—Details of Tests

Required Tests

17. The tests specified in Sections 5, 6 and 7 shall be conducted in accordance with the requirements of Table II for each size and classification of electrodes using the positions of welding and types of current shown; all of the details of testing shall conform to the requirements of this Part II.

Material for Test Plates

18. Steel to be used for test plates shall conform to one of the following specifications of the American Society for Testing Materials:

(*a*) Standard Specifications for Low and Intermediate Tensile Strength Carbon-Steel Plates of Flange and Firebox Qualities (Plates 2 in. and Under in Thickness) Grade C (A.S.T.M. Designation: A 285).[3] or

(*b*) Standard Specifications for Steel for Bridges and Buildings (A.S.T.M. Designation: A 7),[4] open-hearth or electric furnace steel.

[3] 1947 Supplement to Book of A.S.T.M. Standards, Part I-A.
[4] 1946 Book of A.S.T.M. Standards, Part I-A.

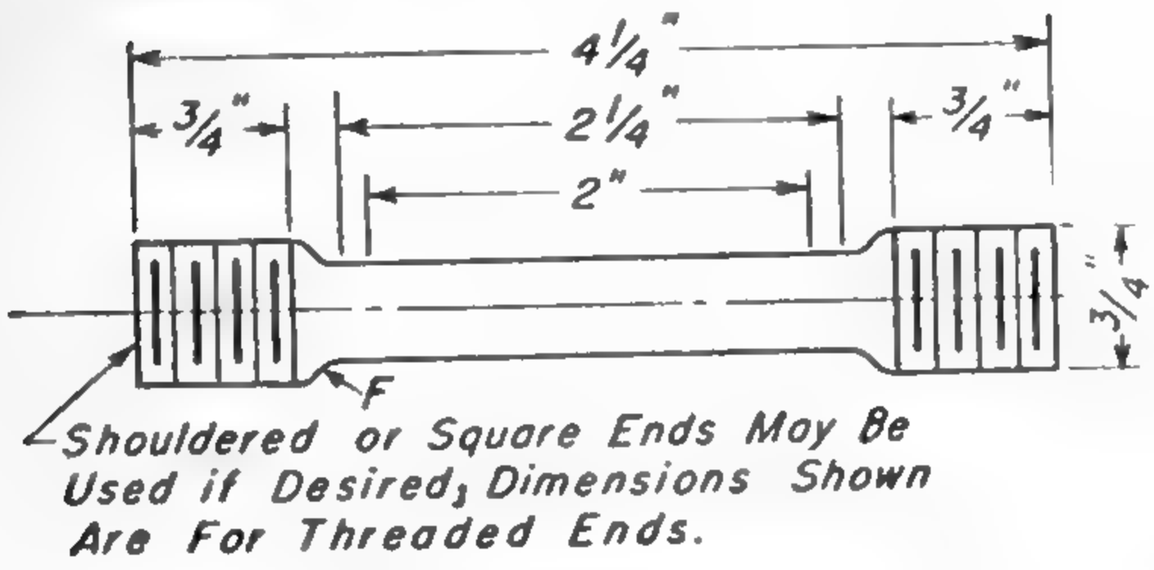
All-Weld-Metal Tension Test

19. (*a*) For electrodes $\frac{5}{32}$ in. and larger a test plate as required by Table II shall be prepared as shown in Fig. 3. The plate shall be insulated from the welding bench by $\frac{1}{2}$ in. of asbestos during welding. After the joint has been tacked, the assembly shall be heated in boiling water for approximately 5 min. prior to welding. The work shall be done in the flat position and in an ambient temperature of not less than 60 F. Weaving shall be the full width of the groove except for the last layer which shall be deposited in two passes.

(*b*) After depositing each pass, the assembly shall be left on the asbestos to cool in still air for a minimum of 5 min. and then immersed in boiling water for approximately 5 min. Each subsequent pass shall be deposited immediately after removal from boiling water. After the last pass, the assembly shall be removed from boiling water after the 5-min. period.

(*c*) If it is necessary to interrupt the pass sequence prescribed in Paragraph (*b*) the assembly shall be removed from the boiling water after a 5-min. period and allowed to cool in still air at room temperature. When ready to resume

Type of Layers for Testing Electrodes	Electrode Size, in.	Test Plate Thickness, *T*, in.	Backing, *B*, in.
Each Layer or Pass not to Exceed ⅛ in. in Thickness.	5/32 3/16 1/4 5/16	3/4 3/4 1 1 1/4	1/4 1/4 1/2 1/2



Tension Test Specimen

Test Plate Showing Location of Test Specimen

FIG. 3.—Requirements for Preparation of All-Weld-Metal Tension Test Specimens.

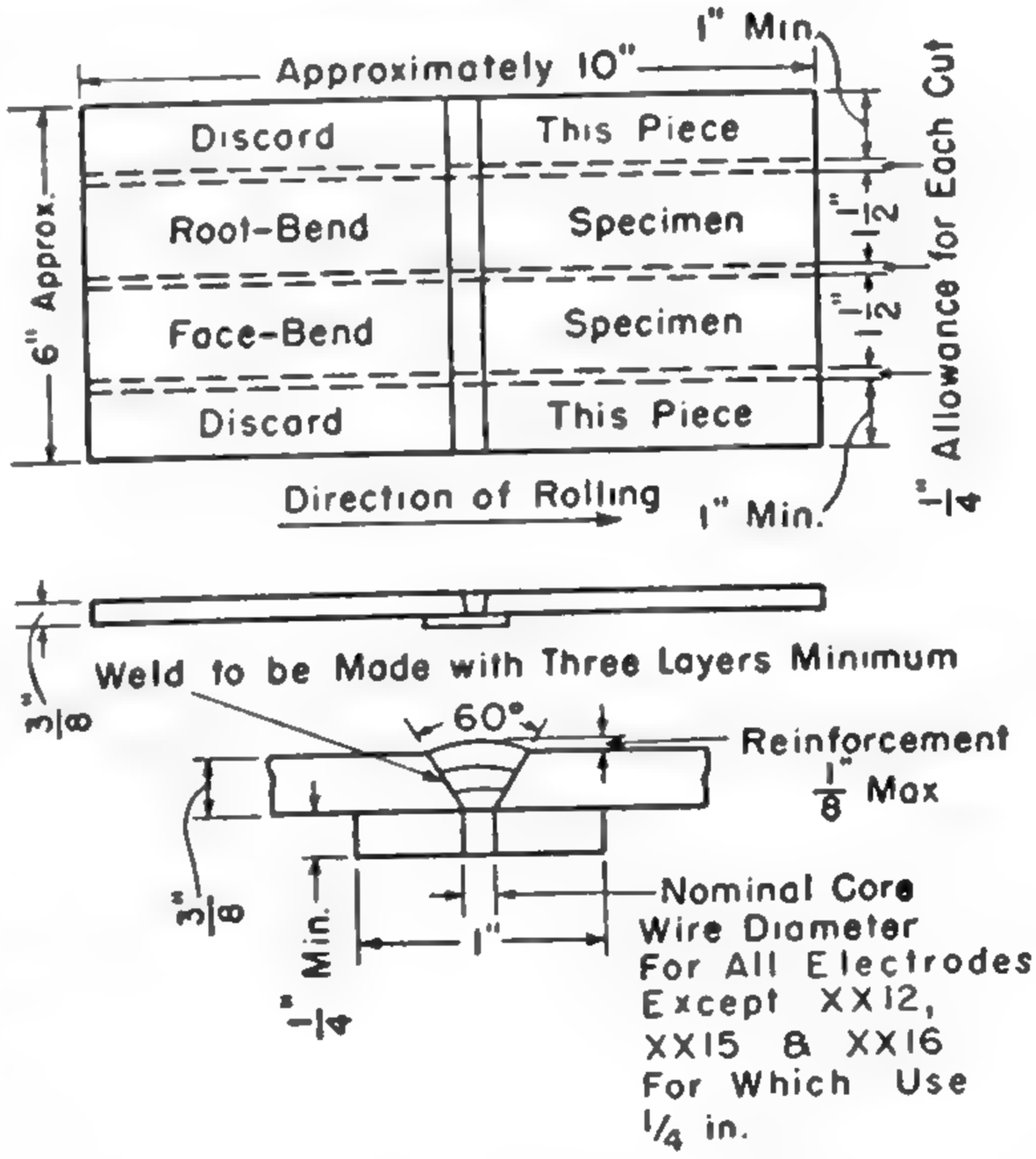
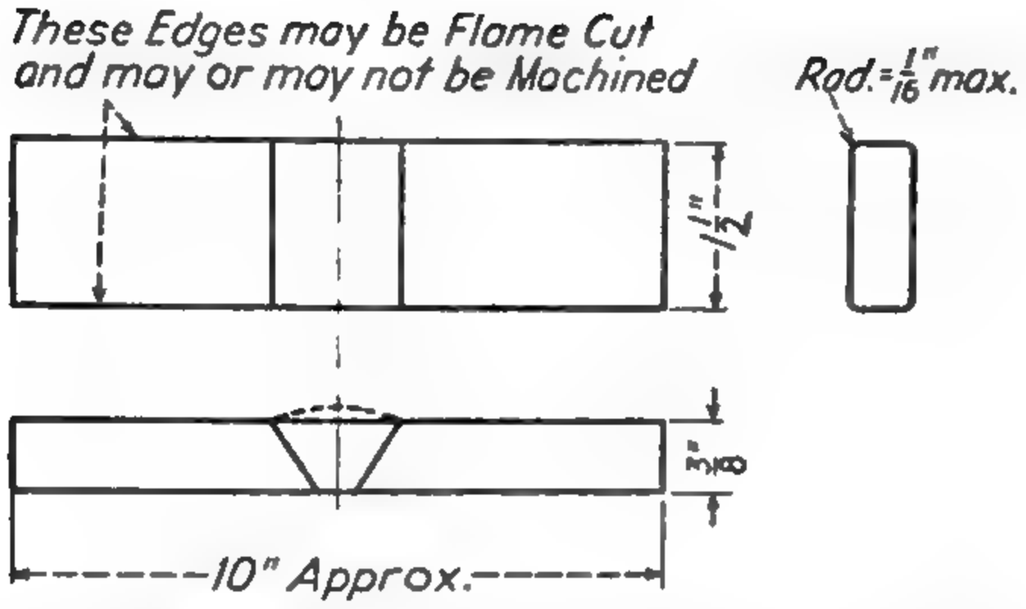


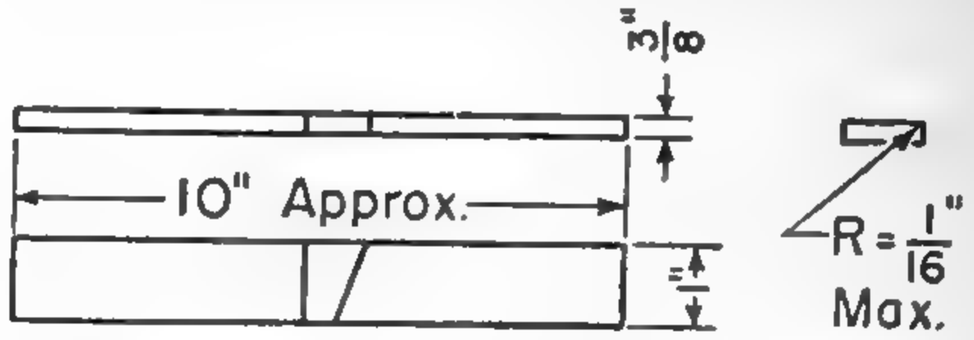
FIG. 4.—Test Joint for Guided-Bend Test.



NOTE.—Weld reinforcement and backing strip shall be removed flush with the surface of the specimen. Machining or grinding shall be done lengthwise on the specimen. The surface of the specimen to be tested shall be finely machined or ground.

FIG. 5.—Face- and Root-Bend Specimens.

be so restrained or preset that warping due to welding will not cause the finished



NOTE.—Specimens shall be sawed or machined from test joint. Weld reinforcement and backing strip shall be removed flush with the surface of the specimen. Machining or grinding shall be done lengthwise on the specimen. The surface of the specimen to be tested shall be finely machined or ground.

FIG. 7.—Side-Bend Specimen.

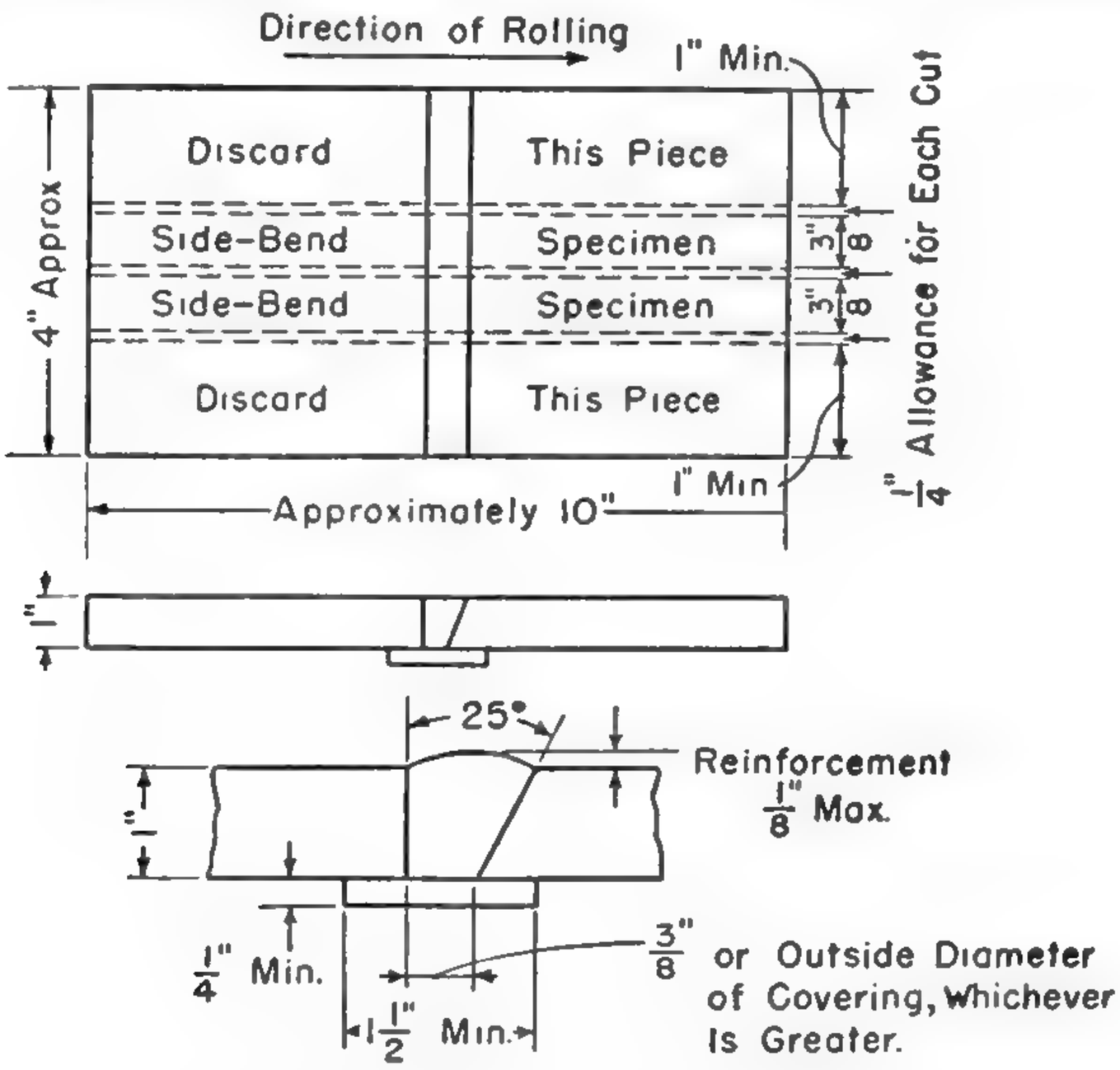


FIG. 6.—Test Joint for Side-Bend Test.

work, the assembly shall be preheated in boiling water for a period of 5 min.

(*d*) One all-weld-metal tension test specimen shall be machined from each finished test assembly as shown in Fig. 3. No stress relieving shall be performed on the test assembly nor on the specimen removed therefrom.

Guided-Bend Test

20. (*a*) When a classification of electrode permits its use with more than one type of current (or polarity), it shall be tested using each type of current (and polarity). The required test plates shall

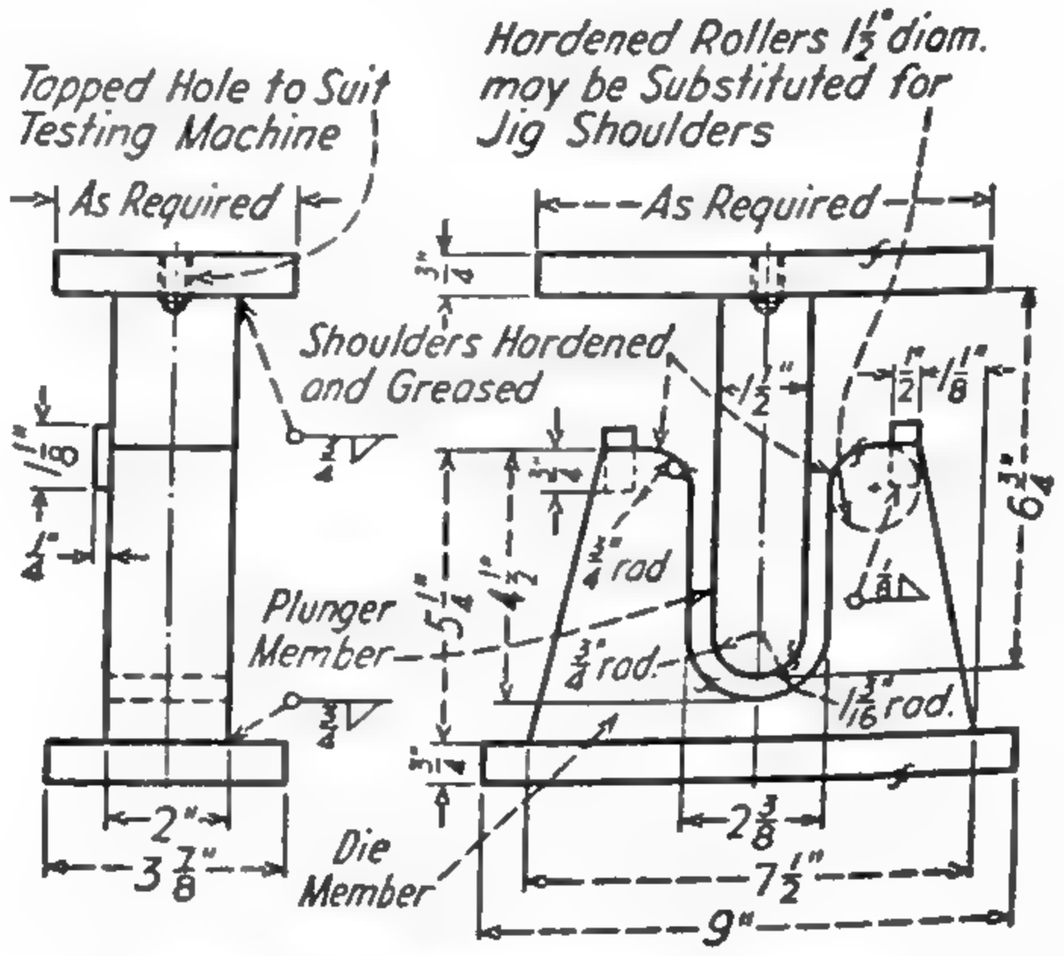


FIG. 8.—Guided-Bend Test Jig.

test plate to be out of line by more than 5 deg.

(*b*) For electrodes $\frac{5}{32}$ and $\frac{3}{16}$ in. in diameter a test joint conforming to the requirements of Fig. 4 shall be prepared in the welding positions and using the types of current (and polarity if d.c.) shown in Table II. The first pass shall be started with the test assembly at a temperature between 60 and 100 F. No stress relieving shall be performed on the test assembly nor on the specimens removed therefrom. From each completed test assembly one face-bend and one root-bend specimen shall be removed as shown in Fig. 4 and prepared for testing as shown in Fig. 5.

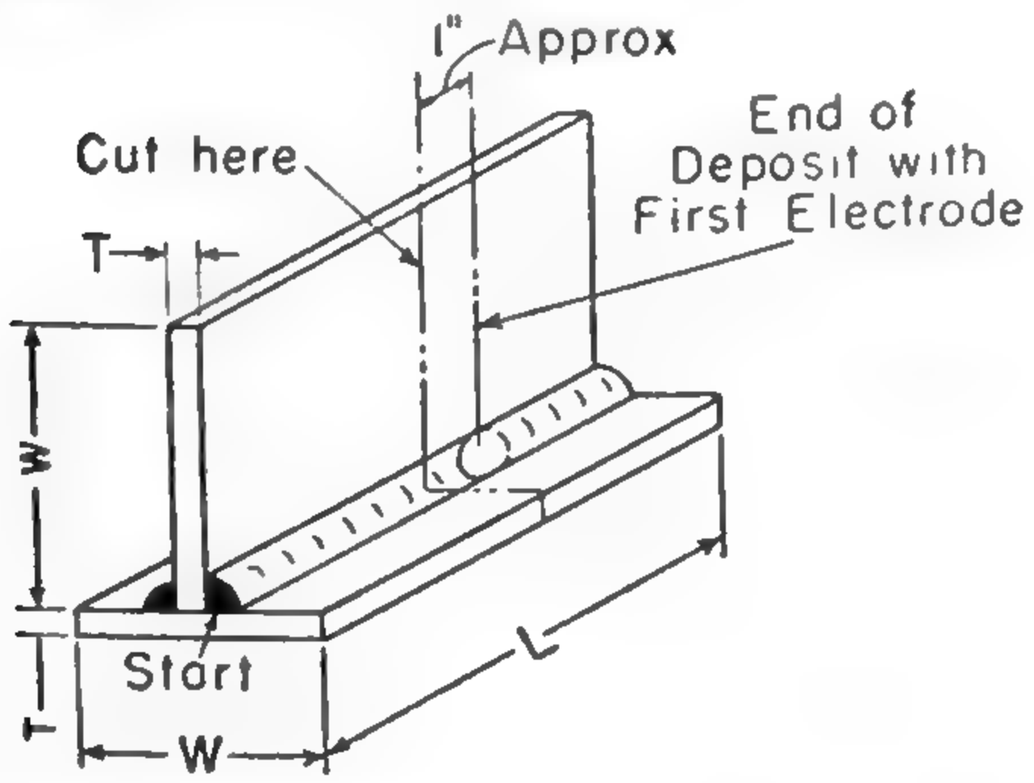
(*c*) For electrodes $\frac{1}{4}$ and $\frac{5}{16}$ in. in diameter, a test joint conforming to the requirements of Fig. 6 shall be prepared in the flat position using the types of current (and polarity if d.c.) shown in Table II. The first pass shall be started with the test assembly at a temperature between 60 and 100 F. No stress relieving shall be performed on the test assembly nor on the specimens removed therefrom. From each completed test assembly two side-bend specimens shall be removed as shown in Fig. 6 and prepared for testing as shown in Fig. 7.

(*d*) Each of the face-, root- and side-bend specimens shall be bent in a jig having the working contour shown in Fig. 8, and otherwise substantially in ac-

TABLE IV.—REQUIREMENTS FOR PREPARATION OF FILLET-WELD TEST ASSEMBLIES.

Electrode Classification Number	Diameter, in.	Plate Size[a]			Position of Welding	Size of Fillet, in.
		Thickness, *T*	Width, *W*	Length, *L*		
E6010, E6011	$\frac{1}{16}$ to $\frac{1}{8}$, incl.	not required	...	...	...	...
	$\frac{5}{32}$	$\frac{1}{4}$	3	12	V and OH	$\frac{3}{16}$ max.
	$\frac{3}{16}$	$\frac{3}{8}$	3	18	V and OH	$\frac{1}{4}$ max.
	$\frac{7}{32}$	not required	...	...	...	...
	$\frac{1}{4}$	$\frac{1}{2}$	3	18	H	$\frac{1}{4}$ min.
	$\frac{5}{16}$	not required	...	...	...	...
E6012, E6013	$\frac{1}{16}$ to $\frac{1}{8}$, incl.	not required	...	...	...	...
	$\frac{5}{32}$	$\frac{1}{4}$	3	12	V and OH	$\frac{1}{4}$ max.
	$\frac{3}{16}$	$\frac{3}{8}$	3	18	V and OH	$\frac{5}{16}$ max.
	$\frac{7}{32}$	not required	...	...	...	...
	$\frac{1}{4}$	$\frac{1}{2}$	3	18	H	$\frac{5}{16}$ min.
	$\frac{5}{16}$	not required	...	...	...	...
E6015, E6016	$\frac{1}{16}$ to $\frac{1}{8}$, incl.	not required	...	...	...	...
	$\frac{5}{32}$	$\frac{1}{4}$	3	12	V and OH	$\frac{1}{4}$ max.
	$\frac{3}{16}$	$\frac{3}{8}$	3	18	H	$\frac{3}{16}$ min.
	$\frac{7}{32}$	not required	...	...	...	...
	$\frac{1}{4}$	$\frac{1}{2}$	3	18	H	$\frac{5}{16}$ min.
	$\frac{5}{16}$	not required	...	...	...	...
E6020	$\frac{1}{16}$ to $\frac{1}{8}$, incl.	not required	...	...	...	...
	$\frac{5}{32}$	$\frac{3}{8}$	3	18	H	$\frac{5}{32}$ min.
	$\frac{3}{16}$	$\frac{3}{8}$	3	18	H	$\frac{3}{16}$ min.
	$\frac{7}{32}$	not required	...	...	...	...
	$\frac{1}{4}$	$\frac{1}{2}$	3	18	H	$\frac{5}{16}$ min.
	$\frac{5}{16}$	not required	...	...	...	...
E6030	not required	...	...	...	...	...

[a] See Fig. 9.

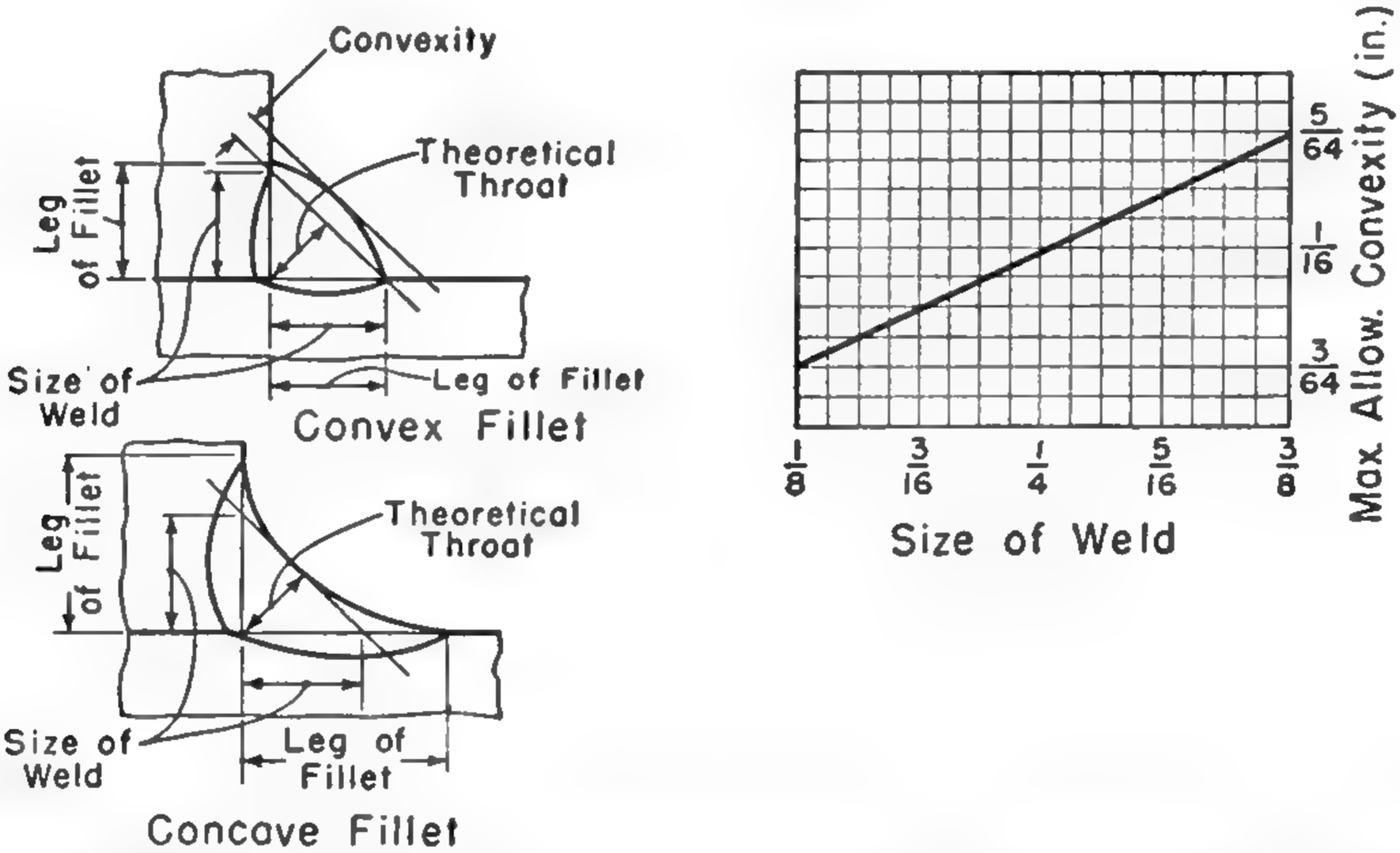


NOTE.—See Table IV for values of *T*, *W*, and *L*.

FIG. 9.—Preparation of Fillet-Weld Test Specimen.

cordance with Fig. 8. Any convenient means may be used for moving the plunger member with relation to the die member. The specimen shall be placed on the die member with the weld at mid-span. Face-bend specimens shall be placed with the face of the weld directed toward the gap; root-bend specimens shall be placed with the root of the weld directed toward the gap; side-bend specimens shall be placed with that side showing the greater defects, if any, as shown in Fig. 9 shall be prepared. The dimensions of the test plates, positions of welding, and sizes of fillet weld shall be as prescribed in Table IV for the particular size and classification of the electrode being tested.

(*c*) In preparing the two plates forming the test assembly, the standing member shall have one edge machined throughout its length so that when it is set upon the base plate, which shall be straight and smooth, there will be intimate contact for the entire length of the joint.



NOTE.—Size of fillet weld = Leg length of largest inscribed isosceles right triangle. Fillet weld size, convexity and leg lengths of fillet welds shall be determined by actual measurement (to nearest 1/64 in.) on a section laid out with scribed lines as shown.

FIG. 10.—Dimensions of Fillet Welds.

directed toward the gap. The two members of the jig shall be forced together until the specimen conforms to a U-shape, and until a wire $\frac{1}{32}$ in. in diameter cannot be placed between the specimen and any point on the curvature of the plunger member of the jig. The specimen shall then be removed from the jig, and the convex surface examined.

Fillet-Weld Test

21. (*a*) When a classification of electrode permits its use with more than one type of current (or polarity), it shall be tested using each type of current (and polarity).

(*b*) A fillet-welded tee-joint assembly

(*d*) A single-pass fillet weld shall be deposited on one side of the joint using the types of current (and polarity if d.c.) prescribed in Table II. When welding in the vertical position is specified, the progression shall be upward. The first electrode used shall be consumed for its full length except for a stub end of not more than 2 in. Additional electrodes, if necessary, shall then be used to complete the weld for the full length of the joint, consuming each electrode completely as stated above—insofar as permitted by the length of the assembly.

(*e*) After completing the weld on the

first side of the joint, the assembly shall be cooled to room temperature (but not less than 60 F.) by any convenient means (Note) before commencing to weld on the second side.

NOTE.—If water is used as the coolant, care should be taken to ascertain that it has been thoroughly removed from the joint.

(*f*) The fillet weld on the second side of the joint shall be deposited by the same procedure as was the first weld.

(*g*) At a point approximately 1 in. back from the crater end of the deposit made with the first electrode on the first side of the joint the specimen shall be cut. Either face may be polished and etched to permit examination.

(*h*) The polished and etched face shall be scribed as shown in Fig. 10 and the size, the leg lengths and the convexity (of convex fillets) shall be determined to the nearest $\frac{1}{64}$ in. by actual measurement.

Hydrogen Test

22. (*a*) Four test specimens shall be prepared by depositing a single bead of weld metal on each of four plates measuring $\frac{1}{2}$ by 1 by approximately 5 in. in length, using $\frac{3}{16}$-in. diameter electrodes. The type of current (and polarity) given in Table II shall apply using a current of 170 to 200 amp. and an arc voltage of 22 to 28 v. The steel used for the test plates shall conform to one of those listed in Section 18. Before welding, the plates shall be thoroughly cleaned and weighed to the nearest 0.1 g.

(*b*) Not more than 1 in. of each electrode shall be burned off on a starting plate immediately prior to depositing weld metal on the test specimen. The weld bead shall be approximately $4\frac{1}{2}$ in. in length, and shall be made by consuming about 5 in. of electrode.

(*c*) Within 30 sec. of completion of welding of each specimen it shall be quenched in water at approximately 70 F. Within 120 sec. of completion of welding, each specimen shall have been cooled, cleaned and placed in an apparatus suitable for collecting hydrogen by displacement of glycerine. All four specimens shall be welded and placed in the hydrogen collecting apparatus within 30 min.

(*d*) The specimens shall be kept immersed in the glycerine for a period of 48 hr., the glycerine being maintained at a temperature of approximately 45 C. (113 F).

(*e*) The specimens, after removal from the glycerine, shall be washed, dried and weighed to the nearest 0.1 g., to determine the amount of weld deposited. The amount of gas evolved shall be determined in terms of cubic centimeters per gram of weld metal.

AMERICAN WELDING SOCIETY
SPECIFICATION A5.2-46T
A.S.M.E. BOILER CONSTRUCTION CODE
SPECIFICATION NO.: SA-251

B. Tentative Specifications for

IRON AND STEEL GAS-WELDING RODS[1]

A.S.T.M. Designation: A 251 - 46 T

ISSUED, 1942; REVISED, 1946.[2]

These Tentative Specifications have been approved by the sponsoring committee and accepted jointly by the A.S.T.M. and the A.W.S. in accordance with established procedures, for use pending adoption as standard. Suggestions for revision should be addressed to the Headquarters of the A.S.T.M., 1916 Race Street, Philadelphia, 3, Pa., or of the A.W.S., 33 W. 39th Street, New York 18, N. Y.

These specifications were prepared jointly by the American Welding Society and the American Society for Testing Materials.

Scope

1. (*a*) These specifications cover gas-welding rods for the welding of carbon and low-alloy steels of weldable quality.

NOTE.—In connection with the welding of low-alloy steels the requirements of these specifications pertain to the tensile strength and elongation of the deposited metal and not to high- or low-temperature characteristics, creep properties, or corrosion resistance.

(*b*) The rods are classified on the basis of the ultimate tensile strength of the deposited weld metal in the stress-relieved condition, as shown in Table I.

Manufacture

2. The rods may be made by any methods that will yield a product conforming to the requirements of these specifications.

Standard Sizes and Length

3. Standard length rods are 36 in., and standard diameters are as follows:

$\frac{1}{16}$ in.	$\frac{5}{32}$ in.	$\frac{5}{16}$ in.
$\frac{3}{32}$ in.	$\frac{3}{16}$ in.	$\frac{3}{8}$ in.
$\frac{1}{8}$ in.	$\frac{1}{4}$ in.	

Chemical Composition

4. The rods shall conform to the following requirement as to chemical composition:

Sulfur, max., per cent.....	0.045

Tension Tests

5. Tension tests shall be made, using $\frac{3}{16}$ or $\frac{1}{4}$-in. welding rods, as prescribed in the following Paragraphs (*a*) to (*e*), these tests qualifying all sizes of welding rod made from the same melt of steel.

(*a*) The steel to be used for test plates shall conform to either of the following

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[1] Under the standardization procedure of the two Societies, these specifications are under the jurisdiction of the A.W.S.-A.S.T.M. Joint Committee on Filler Metal.

[2] Revision accepted by A.S.T.M. Administrative Committee on Standards, July 26, 1946; approved by A.W.S. Board of Directors, June 20, 1946.

These specifications which comprise a portion of the former Tentative Specifications for Iron and Steel Filler Metal (Arc-Welding Electrodes and Gas-Welding Rods) (A 205 - 37 T)) were published as tentative from 1937 to 1940.

specifications of the American Society for Testing Materials:

(*1*) Standard Specifications for Low and Intermediate Tensile Strength Carbon-Steel Plates of Flange and Firebox Qualities (Plates 2 in. and Under in Thickness) (A.S.T.M. Designation: A 285),[3] and

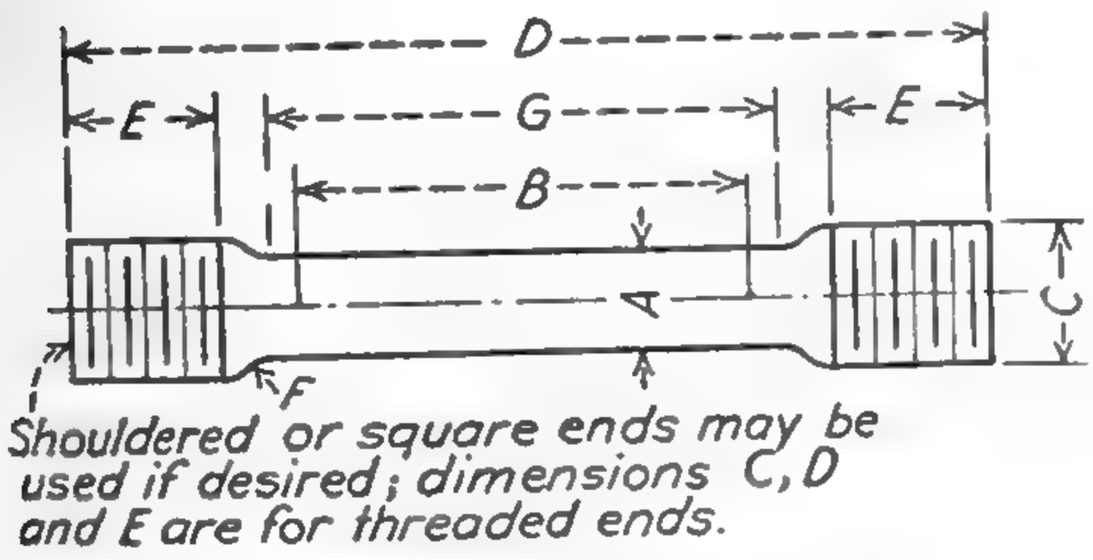
(*2*) Standard Specifications for Steel for Bridges and Buildings (A.S.T.M. Designation: A 7),[3] open-hearth or electric-furnace steel.

(*b*) A test plate shall be prepared as shown in Fig. 1 (for welding rods of the GA65, GA60, GA50, GB65, and GB60 classifications) or Fig. 2 (for welding rods of the GB45 classification). The plate shall be insulated from the welding bench by asbestos during welding. After the joint has been tacked, the plate on both sides of the joint shall be heated for approximately 5 min. with a flame of the size and type to be used in welding the joint. The test plate shall then be welded using a maximum of five layers and having no layer exceeding $\frac{5}{16}$ in. in thickness. The weld metal shall be deposited with a backhand technique,

[3] 1946 Book of A.S.T.M. Standards, Part I-A.

Dimensions of Test Plate and Tension Test Specimen, in.

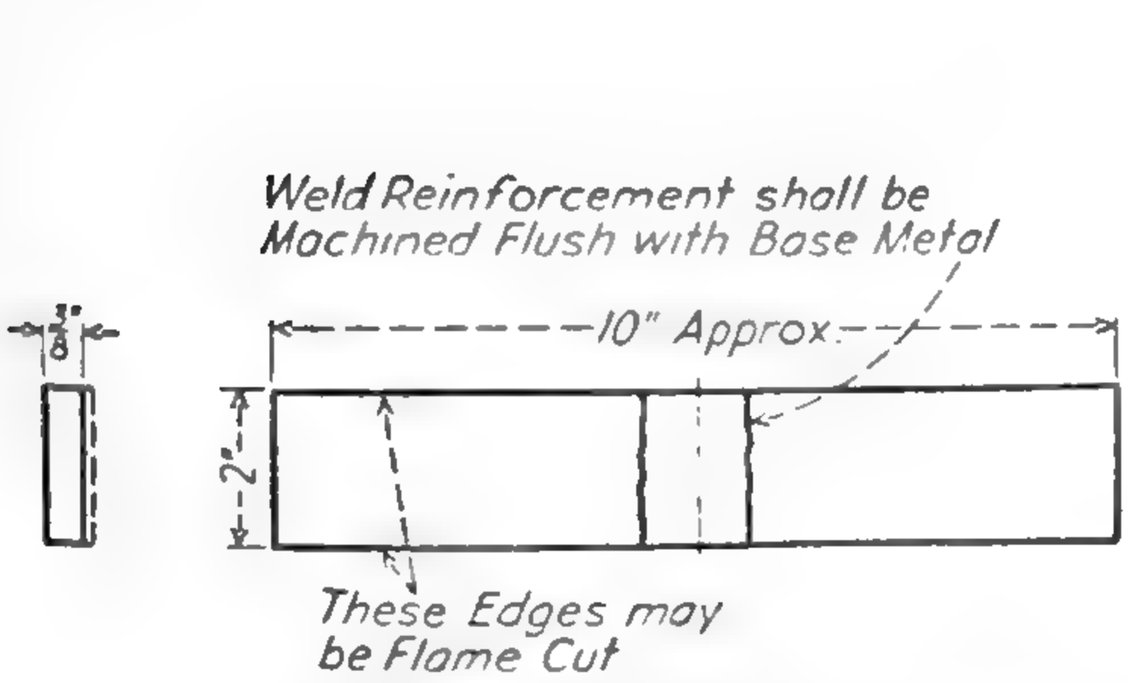
A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*
0.500 ± 0.01	2	¾	4¼	¾	⅜	2¼	12	¾	¼



(*a*) Tension Test Specimen.

(*b*) Test Plate Showing Location of Test Specimens.

FIG. 1.—Requirements for Preparation of All-Weld-Metal Tension Test Specimens.



(*a*) Tension Test Specimen.

(*b*) Test Plate Showing Location of Test Specimens.

FIG. 2.—Requirements for Preparation of Full-Section Tension Test Specimens.

using the size and type of flame recommended by the manufacturer of the welding rod. After depositing each layer, the plate shall be left on the asbestos to cool in still air for at least 15 min. The joint shall be welded completely but shall not have a reinforcement exceeding 20 per cent of the plate thickness. It is permissible to torch normalize the weld by reheating the weld metal above the critical temperature range. After the last pass, the plate shall be left on the asbestos until cold. The work shall be done at room temperature of not less than 60 F. and in the flat position. Test plates shall preferably be so supported that warping due to welding will not cause the finished test plate to be out of line by more than 5 deg. If test plates become warped more than 5 deg. they shall be straightened cold before being stress-relieved, when required.

(*c*) Two tension test specimens shall be machined from the finished test plate as shown in Fig. 1 (for welding rods of the GA65, GA60, GA50, GB65, and GB60 classifications) or Fig. 2 (for welding rods of the GB45 classification), and shall conform to the requirements as to tensile properties prescribed in Table I.

(*d*) If either specimen fails, another test plate shall be welded and both specimens shall conform to the tension test requirements prescribed in Table I.

(*e*) Welding rods in each classification shall be capable of producing satisfactory welds which will conform to the tension test requirements prescribed in Table I.

TABLE I.—TENSILE REQUIREMENTS OF DEPOSITED METAL.

(Using 5/32 or 1/4-in. Welding Rods)

Welding Rod Classification Number	Plate Thickness, in.	Treatment of Welded Specimen[a]	Tension Test Requirements	
			Tensile Strength, min., psi.	Elongation in 2 in., min., per cent
GA65	3/4	SR	65 000	20
		NSR	72 000	17
GA60	3/4	SR	60 000	25
		NSR	62 000	20
GA50	3/4	SR	50 000	28
		NSR	52 000	23
GB65	3/4	SR	65 000	18
		NSR	72 000	15
GB60	3/4	SR	60 000	20
		NSR	62 000	15
GB45	3/8	NSR	45 000[b]	..

[a] The abbreviations SR and NSR signify stress-relieved and non-stress-relieved, respectively. Stress-relieving when prescribed in these specifications is for the purpose of developing the fundamental properties of the weld metal unaltered by locked-up stress. Values obtained from stress-relieved welded specimens are about 5 per cent lower in tensile strength and 10 to 20 per cent higher in elongation than those of non-stress-relieved specimens. Stress-relieving shall be within the range of 1150 ± 25 F. for 1 hr. per inch of thickness. Specimens shall be heated in a suitable furnace at the rate of 300 to 350 F. per hour until a temperature of 1150 ± 25 F. has been attained. After this temperature has been reached, it shall be maintained for 1 hr. for each inch or fraction thereof of the maximum thickness of the section. The specimens shall be cooled at the same rate specified for heating and may be removed from the furnace when the temperature of the plates has reached 300 F.

[b] This value shall be obtained with the full-section tension test specimen shown in Fig. 2. All other values in this column shall be obtained with the all-weld-metal tension test specimen shown in Fig. 1.

Face- and Root-Bend Tests of Welded Joints

6. For all classifications of welding rods, except GB45, face- and root-bend tests shall be made, using 3/16 or 1/4-in. welding rods, as prescribed in the following Paragraphs (*a*) to (*f*), these tests qualifying all sizes of welding rod made from the same melt of steel.

(*a*) The steel to be used for test plates shall conform to either of the specifications listed in Section 5 (*a*).

(*b*) A test plate shall be prepared as shown in Fig. 3. The work shall be done at room temperature of not less than 60 F. and in the flat position. No stress-relieving shall be performed on the test plate or on the specimens removed therefrom.

(*c*) From each test plate there shall be removed two face-bend specimens and two root-bend specimens in the order shown in Fig. 3. The specimens shall be prepared for testing as shown in Fig. 4.

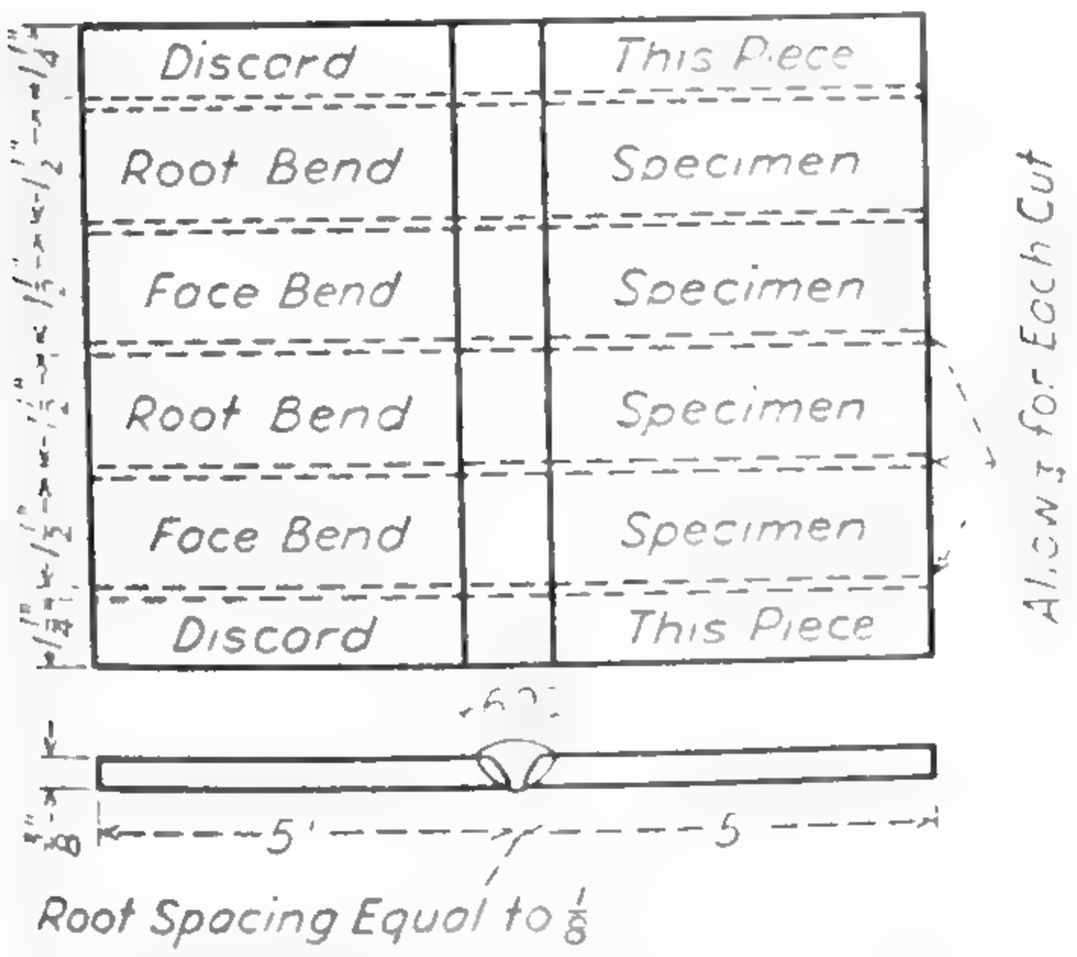
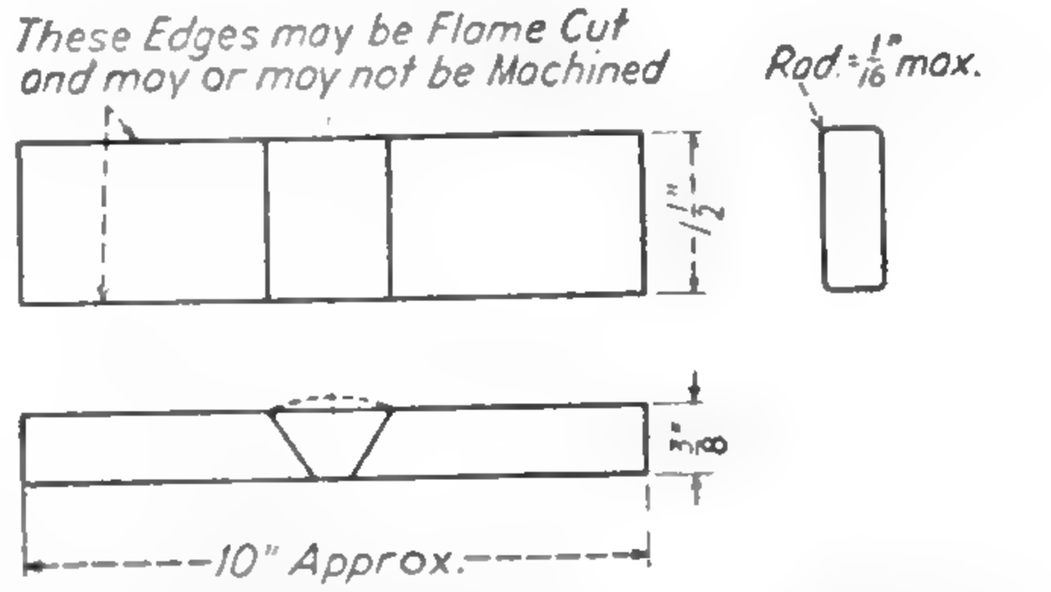


FIG. 3.—Requirements for Preparation of Test Plate for Face- and Root-Bend Tests.

(*d*) Each specimen shall be bent in a jig having the working contour shown in Fig. 5, and otherwise substantially in accordance with that figure. Any convenient means may be used for moving the plunger member with relation to the die member. The specimen shall be placed on the die member of the jig with the weld at mid-span. Face-bend specimens shall be placed with the face of the weld directed toward the gap, and root-bend specimens shall be placed with the root of the weld directed toward the gap. The two members of the jig shall be forced together until the specimen conforms to a U-shape, and until a wire $\frac{1}{32}$ in. in diameter cannot be placed between the specimen and any point on the curvature of the plunger member of the jig. The specimen shall then be removed from the jig.



NOTE.—Weld reinforcement shall be removed flush with the surface of the specimen. Machining shall be done lengthwise of the specimen. The surface of the specimen to be tested shall be finely machined or ground.

FIG. 4.—Face- and Root-Bend Specimens.

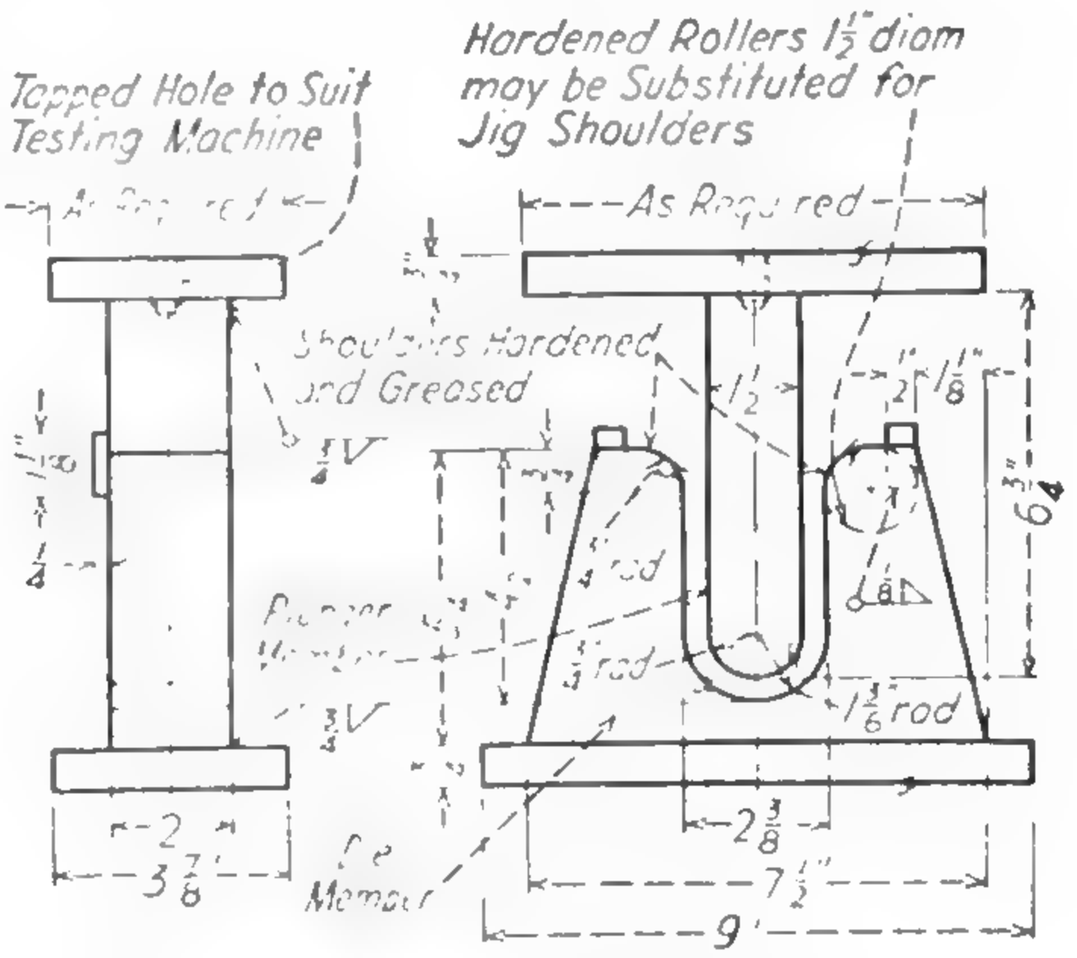


FIG. 5.—Guided-Bend Test Jig.

(*e*) The convex surface of each specimen shall be examined for the appearance of cracks or other open defects. The specimen shall be considered as having failed if a crack or other open defect, exceeding $\frac{1}{8}$ in. measured in any direction, is present after the bending. Cracks occurring on the corners of the specimen during testing shall not be considered.

(*f*) Welding rods of all classifications, except GB45, shall be capable of producing satisfactory welds which will conform to the face- and root-bend test requirements prescribed in Paragraphs (*a*) to (*e*) above, for all positions of welding.

Permissible Variations in Dimensions

7. The diameter of the rod shall not vary more than plus or minus 0.005 in. from the standard size specified. Cut lengths shall not vary from that specified by more than plus 0 or minus $\frac{1}{4}$ in.

Workmanship and Finish

8. (*a*) Rods shall be of uniform quality and free from injurious segregation, oxides, pipe, seams, or other irregularities.

(*b*) Rods shall be cold-drawn to a smooth finish, free from slivers, depressions, scratches, scale, lime, or foreign matter other than oil, except that rods may have a copper coating.

(*c*) The rods shall be carefully oiled with the minimum amount necessary to prevent rusting, except when copper-coated or otherwise treated to prevent rusting.

Packing

9. The rods shall be suitably packed, wrapped, boxed, or crated to protect against injury during shipment or under normal dry storage conditions, as follows:

(*a*) Bundles of 50 or 100 lb. net weight,

(*b*) Boxes or kegs of 50, 100, or 300 lb. net weight.

Marking

10. (*a*) Welding rods $\frac{1}{8}$ in. and over in diameter shall be marked or stamped with positive identification marks at intervals of not more than 18 in. Such marks shall be clearly distinguishable and shall identify the trade designation of the manufacturer or the classification number of the welding rod.

(*b*) All bundles, boxes, or kegs shall be legibly marked with the following information:

(*1*) Classification,

(*2*) Manufacturer's name and trade designation, and

(*3*) Standard size and length.

Guarantee

11. The manufacturer shall make tests at frequent intervals in accordance with the methods prescribed in these specifications, and shall guarantee that the rods in all sizes and classes conform to these specifications, and the marking of the classification number on the container shall be indication of this fact. The manufacturer's responsibility shall be limited to replacement of any rods which do not conform to the requirements of these specifications.

C. Tentative Specifications for

ALUMINUM AND ALUMINUM-ALLOY METAL ARC-WELDING ELECTRODES[1]

A.S.T.M. Designation: B 184 – 43 T

ISSUED, 1943.[2]

These Tentative Specifications have been approved by the sponsoring committees and accepted by the Societies in accordance with established procedures, for use pending adoption as standard. Suggestions for revision should be addressed to the Headquarters of the A.S.T.M., 1916 Race St., Philadelphia 3, Pa., or of the A.W.S., 33 W. 39th St., New York 18, N. Y.

These Specifications were prepared jointly by the American Welding Society and the American Society for Testing Materials.

Scope

1. These specifications cover coated or covered metal arc-welding electrodes for welding aluminum and aluminum alloys. The coating or covering is referred to in these specifications as covering.

Manufacture

2. The electrodes may be made by any methods that will yield a product conforming to the requirements of these specifications.

Standard Sizes and Lengths

3. Standard sizes and lengths of electrodes are as shown in the following table. In all cases, standard size refers to the diameter of the core wire.

Electrode Classification Number	Standard Sizes, Diameter of Core Wire, in.	Standard Lengths, in.
Al-2 and Al-43	$\frac{3}{32}$, $\frac{1}{8}$, $\frac{5}{32}$, $\frac{3}{16}$, $\frac{1}{4}$, $\frac{5}{16}$, $\frac{3}{8}$	14 18

Chemical Composition

4. (*a*) The electrode core wire for Al-2 electrodes shall conform to the requirements as to chemical composition prescribed for grade 99+ in the Standard Specifications for Aluminum Ingots for Remelting (A.S.T.M. Designation: B 24)[3] which are shown in Table I.

(*b*) The electrode core wire for Al-43 electrodes shall conform to the requirements as to chemical composition for alloy S2 as prescribed in the Tentative Specifications for Aluminum-Base Alloy Sand Castings (A.S.T.M. Designation: B 26)[3] which are shown in Table I.

[1] Under the standardization procedure of the two Societies, these specifications are under the jurisdiction of the A.W.S.-A.S.T.M. Joint Committee on Filler Metal.

[2] Accepted by the A.S.T.M. at annual meeting, June, 1943; approved by A.W.S. Board of Directors, June 10, 1943.

[3] 1942 Book of A.S.T.M. Standards, Part I, page 1115.

TABLE I.—CHEMICAL REQUIREMENTS.

NOTE.—Analysis shall be made only for the elements specifically mentioned in this table. If, however, the presence of other elements is indicated in the course of routine analysis, further analysis shall be made to determine that the total of these other elements is not present in excess of the limits specified for "total other impurities" in the last item in the table.

	Electrode Classification	
	Al-2	Al-43
Copper, max., per cent	0.2	0.4
Iron, max., per cent	0.6	0.8
Silicon, per cent	0.5 max.	4.5 to 6.0
Magnesium, max., per cent	0.05	0.05
Manganese, max., per cent	0.05	0.3
Zinc, max., per cent	0.05	0.2
Titanium, max., per cent	0.03	0.2
Nickel, max., per cent	0.03	
Aluminum, per cent	99.0 min.	remainder
Total other impurities, per cent	0.1[a]	0.3

[a] None of the elements included in "total other impurities" shall exceed 0.03 per cent maximum.

Weld Tests

5. (*a*) To determine the suitability of the electrodes for producing welds of adequate strength, ductility, and soundness, tension and bend tests shall be conducted as prescribed in the following Sections 6 to 8.

(*b*) For electrodes $\frac{5}{32}$ in. and smaller, the performance of these sizes shall be judged by the performance of $\frac{5}{32}$-in. electrodes of the same classification. For electrodes $\frac{3}{16}$ in. and larger the performance shall be judged by the performance of $\frac{1}{4}$-in. electrodes of the same classification.

Preparations of Test Specimens

6. (*a*) A test plate shall be prepared as shown in Fig. 1, using the size of electrode prescribed in Section 5 (*b*). The material for the test plate shall conform to the following specifications of the American Society for Testing Materials:

(*1*) *For Testing Electrodes of Classification No. Al-2.*[3a]—Alloy A2 as prescribed in the Tentative Specifications for Aluminum and Aluminum-Alloy Sheet and Plate (A.S.T.M. Designation: B 209).[3]

(*2*) *For Testing Electrodes of Classification No. Al-43.*[4]—Alloy Ml as prescribed in the Tentative Specifications for Aluminum and Aluminum-Alloy Sheet and Plate for Use in Pressure Vessels (A.S.T.M. Designation: B 178).[3]

(*b*) The plate shall be preheated before welding to between 350 and 400 F. All welding shall be done from one side in the flat position. No stress relieving or other thermal treatment shall be done after welding. Test plates shall preferably be so supported that warping due to welding will not cause the finished test plate to be out of line by more than 5 deg. If test plates become warped more than 5 deg., they shall be straightened cold.

(*c*) Two reduced-section tension specimens, one guided-face-bend specimen,

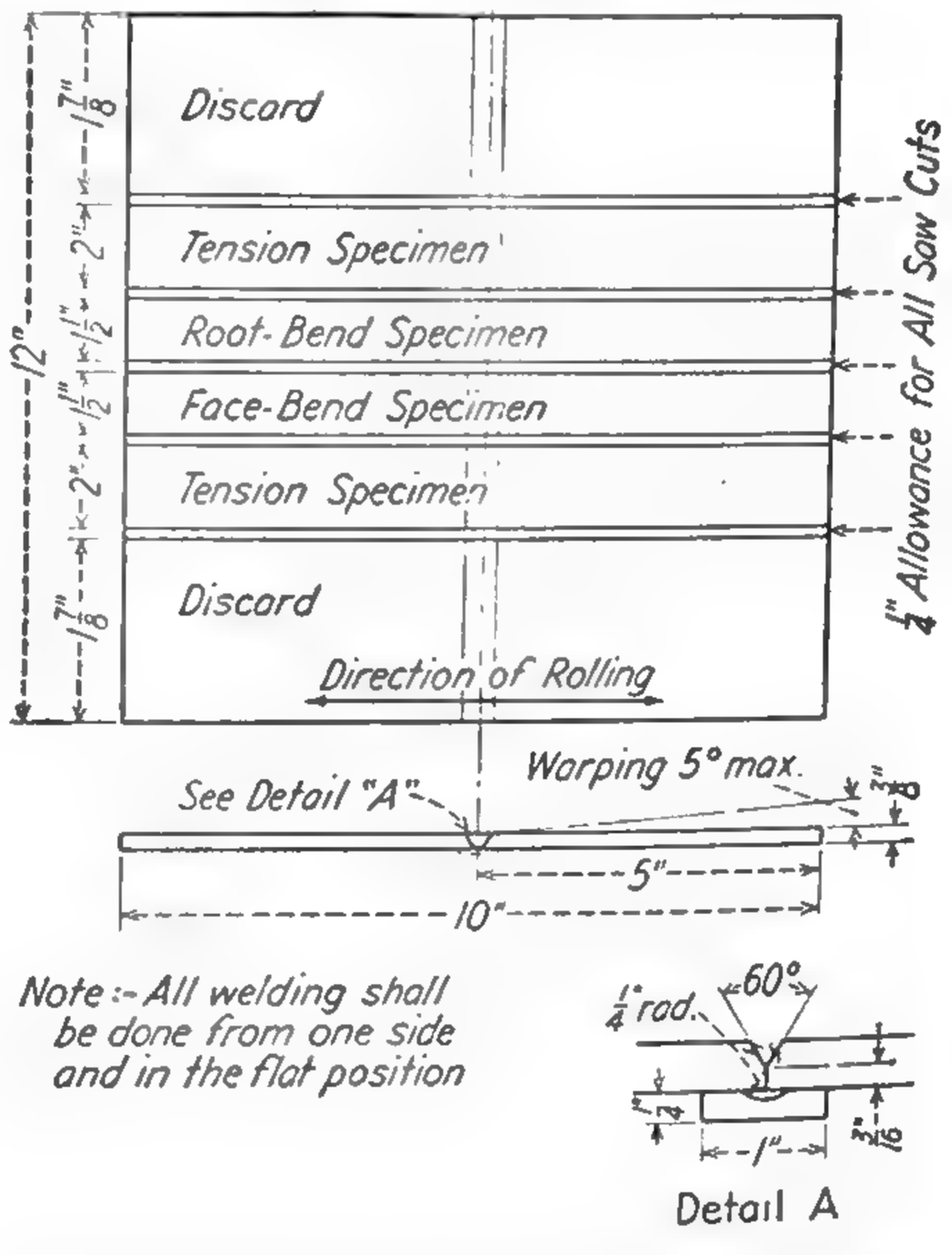


FIG. 1.—Requirements for Preparation of Test Plate for Face- and Root-Bend Specimens.

and one guided-root-bend specimen shall be machined from the finished test plate as shown in Fig. 2. These specimens are in accordance with specimens H-1, E-1, and F-1, respectively, of the A.W.S.

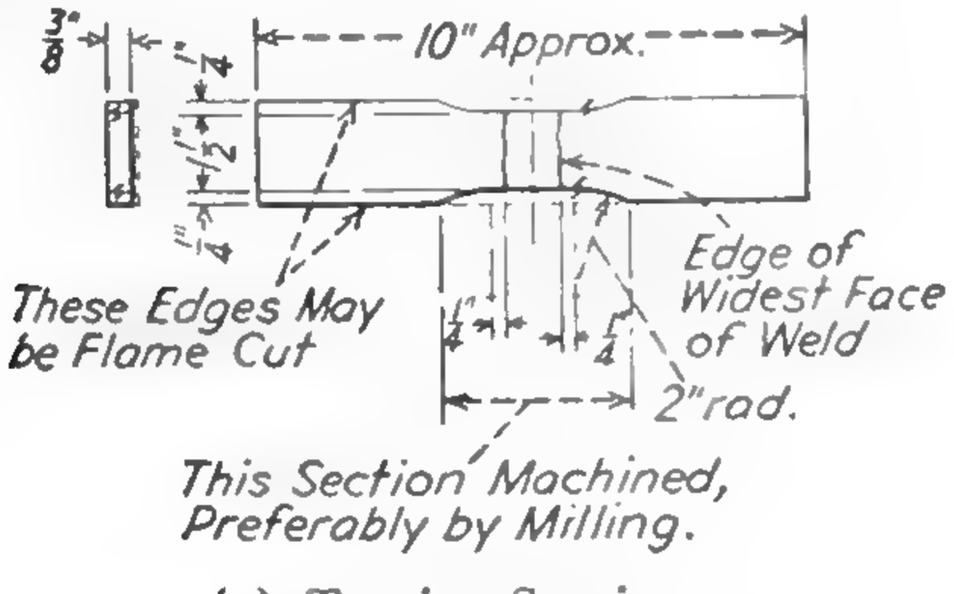
[3a] Editorially revised in 1946. Alloy A2 of A.S.T.M. Specifications B209 is identical with the alloy covered by the former A.S.T.M. Specifications B25; which was discontinued in 1946.

[4] Editorially revised in 1949. Alloy Ml of A.S.T.M. Specifications B 178 is identical with the alloy covered by the former A.S.T.M. Specifications B 126. which was discontinued in 1947.

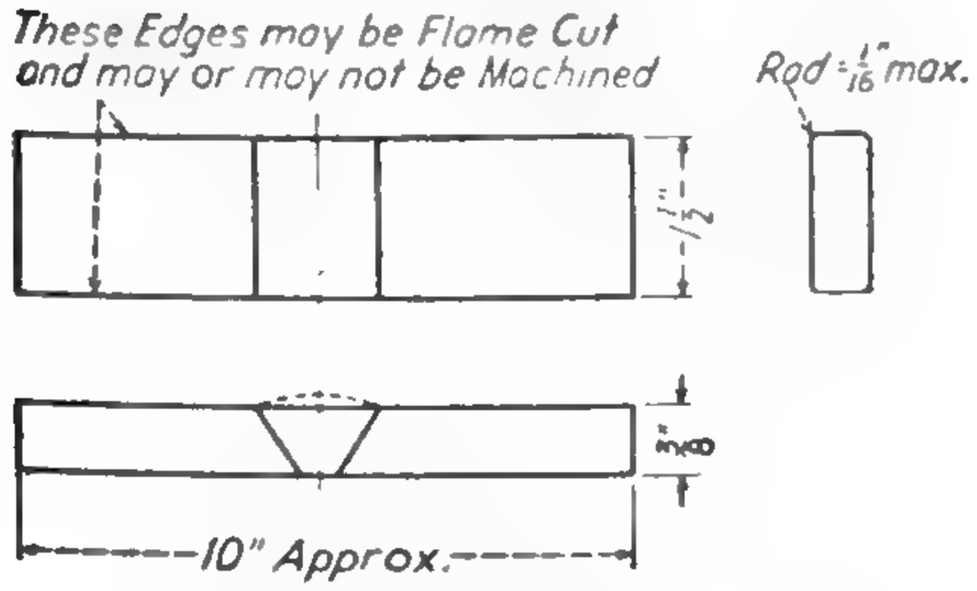
Standard Methods for Mechanical Testing of Welds.[5]

Tension and Bend Test Procedures

7. (*a*) *Reduced-Section Tension Specimens.*—Before testing, the least width and corresponding thickness of the reduced section of the test specimen shall be measured in inches. The cross-sectional area shall be obtained by multiplying the width by the thickness. The specimen shall be ruptured by a tension load and the maximum load in pounds determined. The tensile strength in pounds per square inch shall be calculated by dividing the maximum load by the cross-sectional area.



(*a*) Tension Specimen.



(*b*) Face-and-Root-Bend Specimens.

FIG. 2.—Details of Test Specimens.

NOTE.—Weld reinforcement shall be removed flush with the base metal; undercut shall not be removed. All machining shall be done transverse to the weld.

Tension corners of bend specimens shall be broken slightly with a file.

All specimens shall be plainly marked on both ends.

(*b*) *Guided-Root- and Face-Bend Specimens.*—Each specimen shall be bent in a jig having the working contour shown in Fig. 3, and otherwise substantially in accordance with that figure. Any convenient means may be used for moving the plunger member with relation to the die member. The specimen shall be placed on the die member of the jig with the weld at mid-span. Face-bend specimens shall be placed with the face of the weld directed toward the gap, and root-bend specimens shall be placed with the root of the weld directed toward the gap. The two members of the jig shall be forced together until the specimen conforms to a U-shape, and until a wire $\frac{1}{32}$ in. in diameter cannot be placed between the specimen at any point on the curvature of the plunger member of the jig. The specimen shall then be removed from the jig.

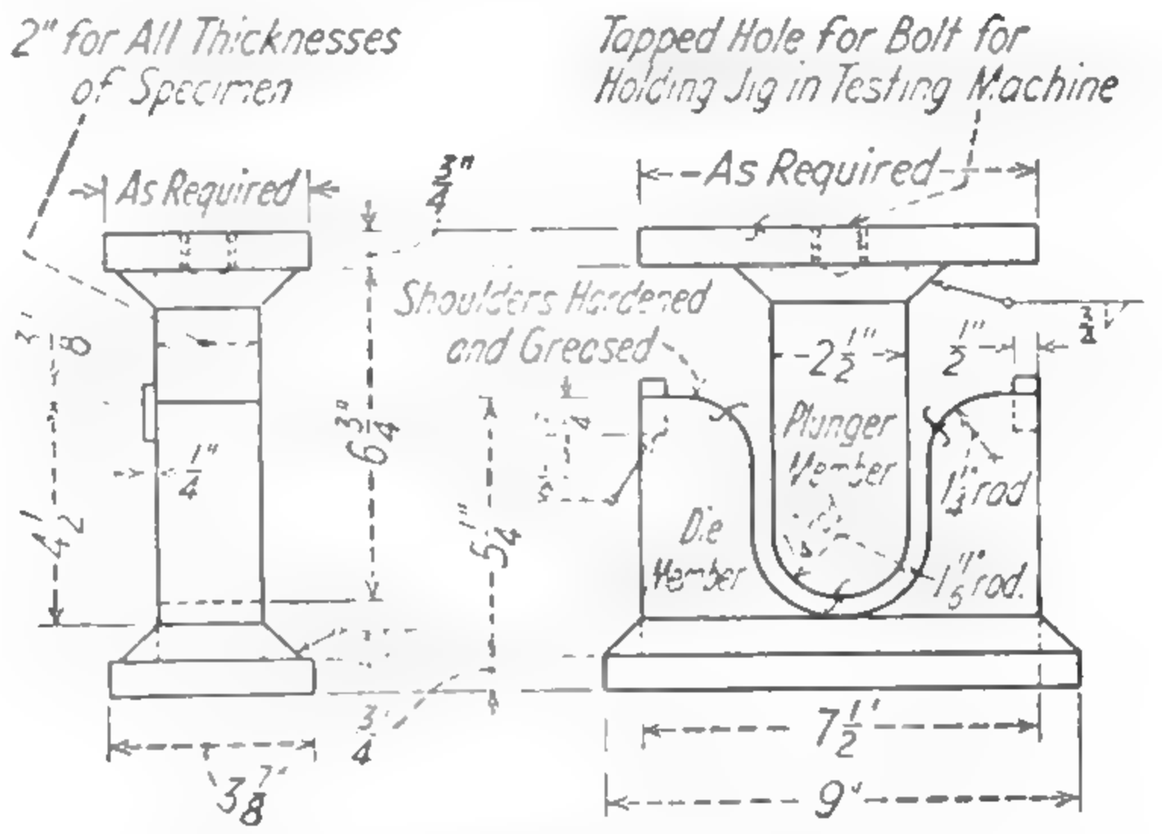


FIG. 3.—Guided-Bend-Test Jig.

Hardened rolls may be used on shoulders if desired. Specific dimensions for 3/8-in. specimen.

Test Results Required

8. (*a*) *Reduced-Section Tension Tests.*—For electrodes of classification No. A1-2, the tensile strength of each specimen tested shall be not less than 12,000 psi. For electrodes of classification No. A1-43, the tensile strength of each specimen shall be not less than 14,000 psi.

(*b*) *Guided Root- and Face-Bend Tests.*—The convex surface of the bend test specimens shall be examined for the appearance of cracks or other open defects. Any specimen in which a crack or other open defect is present after bending, exceeding $\frac{1}{8}$ in. measured in any direction, shall be considered as having failed. Cracks occurring on the corners of the specimen during testing shall not be considered.

[5] 1942 Welding Handbook, p. 1121, Am. Welding Society.

Permissible Variations in Dimensions

9. (*a*) Electrodes shall be bare or free from covering for a distance of about 1 in. but not more than $1\frac{1}{4}$ in., for making contact with the holder.

(*b*) The arc end of each electrode shall either be bare or the coating easily removable with the fingers to permit easy striking of the arc. The length of any bare portion of the arc end, measured from the end to the point where the full cross-section of the coating obtains, shall not exceed one core-wire diameter or in any case $\frac{1}{8}$ in.

(*c*) The diameter of the core wire shall not vary more than plus or minus 0.002 in. from the standard size specified. The length shall not vary more than plus or minus $\frac{1}{8}$ in. from that specified.

Electrode Coverings

10. (*a*) Electrodes shall be suitable for making butt and fillet welds in the flat position and for making butt welds in the vertical position.

(*b*) The coverings shall have sufficient electrical resistance at or below 100 F. to insulate effectively against a difference of potential of 100 v.

(*c*) The coverings shall during welding be consumed uniformly on all sides and shall not blister or burn back from the core wire.

(*d*) The slag produced shall be readily removable.

(*e*) The fumes given off from the covering when used in well-ventilated places shall not be injurious to the health of the welding operator.

(*f*) The coverings shall not blister when heated to 400 F.

Workmanship

11. (*a*) The core of electrodes shall be of uniform quality and free from injurious segregation, oxides, pipe, seams, or other irregularities.

(*b*) The coverings on electrodes shall be such that they are not readily damaged by ordinary handling and shall be of commercially uniform thickness and shall present a workmanlike appearance. Coverings shall be free from injurious scabs, blisters, abnormal pockmarks, bruises, or other surface defects.

Packing

12. (*a*) Electrodes shall be suitably wrapped, packed, boxed, or crated to insure against mechanical damage during shipment or storage. The method of packaging shall be such as to protect the flux coating from absorbing moisture. All packages shall be dated at the time of packing.

(*b*) Standard packages shall be 1 lb. or 10 lb. One-pound pakcages shall be packed in moisture-resistant wrappings. Ten-pound packages shall be packed in moisture-resistant wrappings, or shall be hermetically sealed, containing ten 1-lb. packages in moisture-resistant wrappings.

Marking

13. All bundles, packages, or boxes, shall be legibly marked with the following information:

(*a*) Name of article,

(*b*) Classification number,

(*c*) Manufacturer's name and trade designation,

(*d*) Standard size, length, and net weight, and

(*e*) Guarantee.

Guarantee

14. The manufacturer shall make tests at frequent intervals in accordance with the methods prescribed in these specifications, and shall guarantee that the electrodes in all sizes and classes conform to these specifications and each container shall be so marked. The manufacturer's responsibility shall be limited to replacement of any electrodes which do not conform to the requirements of these specifications.

AMERICAN WELDING SOCIETY
SPECIFICATION A5.4-48T

D. Tentative Specifications for

CORROSION-RESISTING CHROMIUM AND CHROMIUM-NICKEL STEEL WELDING ELECTRODES[1]

A.S.T.M. Designation: A 298 – 48 T

ISSUED, 1946; REVISED, 1948.[2]

These Tentative Specifications have been approved by the sponsoring committee and accepted by the Cooperating Societies in accordance with established procedures, for use pending adoption as standard. Suggestions for revisions should be addressed to the Headquarters of the A.S.T.M., 1916 Race St. Philadelphia 3, Pa., or of the A.W.S., 33 W. 39th St., New York 18, N. Y.

These specifications were prepared jointly by the American Welding Society and the American Society for Testing Materials.

Scope

1. These specifications prescribe requirements for covered chromium and chromium-nickel steel electrodes yielding deposited weld metal in which chromium exceeds 4 per cent and nickel does not exceed 50 per cent.

NOTE.—No attempt has been made to classify all grades of electrodes within the limits of the above scope; only the more commonly used have been included.

PART I.—CLASSIFICATION AND ACCEPTANCE

Classification

2. (*a*) The electrodes are classified on the basis of chemical analysis of the weld metal and usability characteristics as specified in Table I.

(*b*) Any electrode classified under one classification shall not be classified under any other classification.

NOTE.—The test requirements of these specifications establish minimum quality levels which will assure suitability of the electrode for the usual applications. The Guide appended to these specifications describes the more common applications and suggests test procedures should the intended application warrant additional tests.

Manufacture

3. The electrodes may be made by any method which will yield a product conforming to the requirements of these specifications.

Chemical Composition

4. The electrodes shall be capable of depositing weld metal conforming to the requirements as to chemical composition prescribed in Table II.

[1] Under the standardization procedure of the two societies, these specifications are under the jurisdiction of the A.W.S.-A.S.T.M. Joint Committee on Filler Metal.

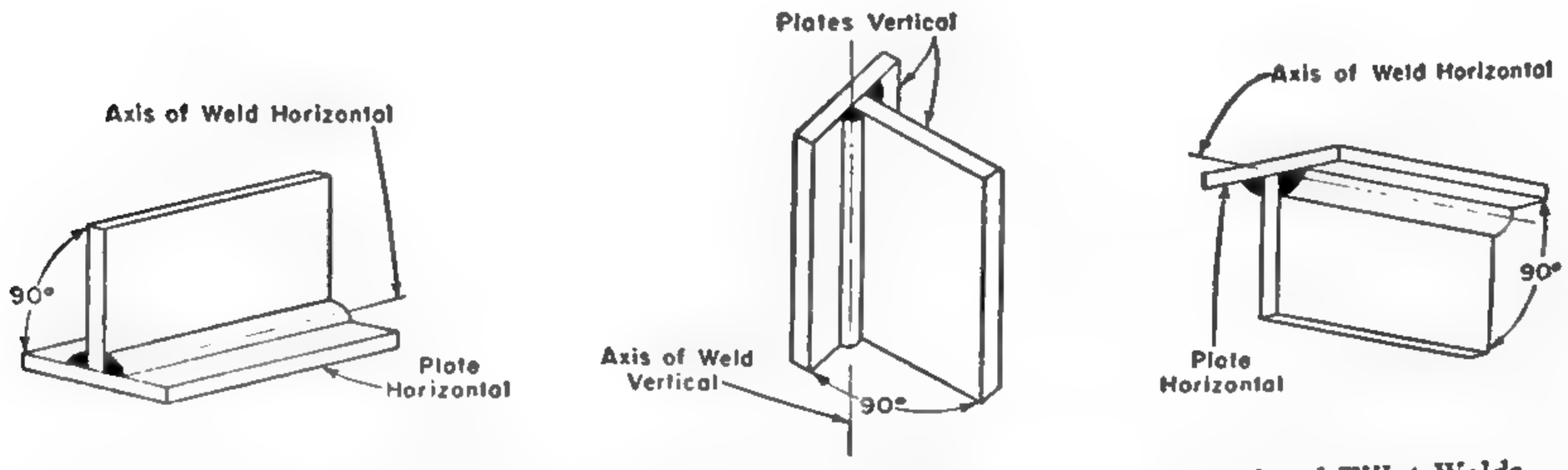
[2] Revision accepted by the A.S.T.M. Administrative Committee on Standards, August 3, 1948; approved by the A.W.S. Board of Directors, June 23, 1948.

TABLE I.—USABILITY CHARACTERISTICS OF ELECTRODES.

	Classification No.	Current[a]	Position of Welding[b]
E308 Series	E308-15	d.c.	F, V, OH, H
	E308-16	a.c. or d.c.	
	E308-25	d.c.	H-Fillets, F
	E308-26	a.c. or d.c.	
E309 Series	E309-15	d.c.	F, V, OH, H
	E309-16	a.c. or d.c.	
	E309-25	d.c.	H-Fillets, F
	E309-26	a.c. or d.c.	
E310 Series	E310-15	d.c.	F, V, OH, H
	E310-16	a.c. or d.c.	
	E310-25	d.c.	H-Fillets, F
	E310-26	a.c. or d.c.	
E316 Series	E316-15	d.c.	F, V, OH, H
	E316-16	a.c. or d.c.	
	E316-25	d.c.	H-Fillets, F
	E316-26	a.c. or d.c.	
E317 Series	E317-15	d.c.	F, V, OH, H
	E317-16	a.c. or d.c.	
	E317-25	d.c.	H-Fillets, F
	E317-26	a.c. or d.c.	
E330 Series	E330-15	d.c.	F, V, OH, H
	E330-16	a.c. or d.c.	
	E330-25	d.c.	H-Fillets, F
	E330-26	a.c. or d.c.	
E347 Series	E347-15	d.c.	F, V, OH, H
	E347-16	a.c. or d.c.	
	E347-25	d.c.	H-Fillets, F,
	E347-26	a.c. or d.c.	
E410 Series	E410-15	d.c.	F, V, OH, H
	E410-16	a.c. or d.c.	
	E410-25	d.c.	H-Fillets, F
	E410-26	a.c. or d.c.	
E430 Series	E430-15	d.c.	F, V, OH, H
	E430-16	a.c. or d.c.	
	E430-25	d.c.	H-Fillets, F
	E430-26	a.c. or d.c.	
E502 Series	E502-15	d.c.	F, V, OH, H
	E502-16	a.c. or d.c.	
	E502-25	d.c.	H-Fillets, F
	E502-26	a.c. or d.c.	

[a] Where d.c. is specified, reversed polarity (electrode positive) is required.
[b] The abbreviations F, H, V, OH, and H-Fillets indicate welding positions (Fig. 1) as follows:

F = Flat
H = Horizontal
H-Fillets = Horizontal Fillets
V = Vertical and
OH = Overhead



(*a*) Horizontal Fillet Welds. (*b*) Vertical Fillet Welds. (*c*) Overhead Fillet Welds.

FIG. 1.—Positions of Test Plates for Welding Fillet-Weld Test Specimens.

Physical Tests

5. (*a*) Physical tests, comprising (*1*) an all-weld-metal tension test to determine the mechanical properties of the deposited metal, and (*2*) a fillet-weld test to demonstrate the usability of an electrode, soundness of weld metal and of fusion zone and proper weld contour, shall be performed at the place of manufacture of the electrodes, for the purpose of classification, when and as prescribed by the electrode manufacturer.

(*b*) At the option and expense of the purchaser any or all of the foregoing tests may be used as a basis for acceptance of electrodes. The fillet-weld test is usually sufficient to determine acceptability.

TABLE II.—CHEMICAL REQUIREMENTS FOR ALL-WELD METAL.

Series	Carbon, max. per cent[a]	Chromium, per cent	Nickel, per cent	Molybdenum, per cent	Columbium, per cent	Manganese, max., per cent	Silicon, max., per cent	Phosphorus, max., per cent	Sulfur, max., per cent
E308.....	0.08	19.0 min.	9.0 min.	...	...	2.50	0.75	0.030	0.030
E309.....	0.15	22.0 min.	12.0 min.	...	...	2.50	0.75	0.030	0.030
E310.....	0.20	25.0 min.	20.0 min.	...	...	2.50	0.75	0.030	0.030
E316.....	0.08	17.0 min.	11.0 min.	1.75 to 2.50	...	2.50	0.75	0.030	0.030
E317.....	0.08	18.0 min.	12.0 min.	3.00 to 4.00	...	2.50	0.75	0.030	0.030
E330.....	0.25	14.0 min.	33.0 min.	...	...	2.50	0.75	0.030	0.030
E347.....	0.08	18.0 min.	9.0 min.	...	10 × C, 1.20 max.	2.50	0.80	0.030	0.030
E410.....	0.12	11.0 min.	0.60 max.	...	...	0.60	0.75	0.030	0.030
E430.....	0.10	15.0 min.	0.60 max.	...	...	0.75	0.75	0.030	0.030
E502.....	0.10	4.0 to 6.0	0.40 max.	0.45 to 0.65	...	0.75	0.75	0.030	0.030

[a] Carbon shall be analyzed to the nearest 0.01 per cent.

TABLE III.—SUMMARY OF TEST REQUIREMENTS.

Electrode			Position of Welding		
Designation (All Series)	Diameter, in.	Current[a]	Chemical Analysis[b]	All-Weld-Metal Tension Test[c]	Fillet Weld Test[d]
—15	1/16, 5/64, 3/32	d.c.	F	not required	not required
	1/8, 5/32	d.c.	F	F	V and OH
	3/16, 1/4	d.c.	F	F	H
—16	1/16, 5/64, 3/32	a.c. and d.c.	F	not required	not required
	1/8, 5/32	a.c. and d.c.	F	F	V and OH
	3/16, 1/4	a.c. and d.c.	F	F	H
—25	1/16, 5/64, 3/32	d.c.	F	not required	not required
	1/8 to 1/4, incl.	d.c.	F	F	H
—26	1/16, 5/64, 3/32	a.c. and d.c.	F	not required	not required
	1/8 to 1/4, incl.	a.c. and d.c.	F	F	H

[a] Where d.c. is specified, reversed polarity (electrode positive) is required.
[b] See Sections 4 and 18.
[c] See Sections 7 and 19.
[d] See Sections 7 and 20.

Methods of Test

6. Test specimens shall be prepared in kind and in number as specified in Table III and tests shall be conducted in accordance with Sections 16 to 20 of these specifications.

Test Requirements

7. In order to be classified under these specifications an electrode shall be capable of yielding the following physical test results in addition to the chemical requirements prescribed in Section 4:

(*a*) The all-weld-metal tension test specimens shall conform to the requirements prescribed in Table IV.

(*b*) The fillet-weld test specimen shall upon examination be found free from cracks or other open defects affecting its strength. Upon examination of the face that has been polished and etched as prescribed, it is required that:

(*1*) Each fillet shall have penetrated to or beyond the junction of the plate edges,

(*2*) Both legs of each fillet weld shall be of equal length within $\frac{1}{16}$ in.,

(*3*) The convexity shall be within the maximum allowable limits prescribed by the graph shown in Fig. 2,

(*4*) The weld and base metal shall show no evidence of cracks, and

(*5*) The weld shall be reasonably free from undercutting, overlap, trapped slag and porosity.

TABLE IV.—TENSILE REQUIREMENTS FOR ALL-WELD METAL.

Series	Tensile Strength, min., psi.	Elongation in 2 in., min., per cent	Heat Treatment
E308	80 000	35	none
E309	80 000	35	none
E310	80 000	30	none
E316	80 000	30	none
E317	80 000	30	none
E330	75 000	25	none
E347	80 000	30	none
E410	70 000	20	[a]
E430	70 000	20	[b]
E502	60 000	20	[a]

[a] Specimen shall be heated to between 1550 and 1600 F. and held for 2 hr., furnace cooled at a rate not exceeding 100 F. per hr. to 1100 F., and air cooled.

[b] Specimen shall be heated to between 1400 and 1450 F. and held for 4 hr., furnace cooled at a rate not exceeding 100 F. per hr. to 1100 F., and air cooled.

Retests

8. Retests may be made in accordance with the following:

(*a*) If the all-weld-metal tension test specimen fails, two additional test assemblies shall be prepared and both specimens shall conform to the requirements as to tensile properties prescribed in Table IV.

(*b*) If the fillet-weld test specimen does not meet the requirements prescribed in Section 7, one additional assembly shall be prepared and tested.

Core Wire and Coverings

9. (*a*) The diameter of the core wire shall not vary more than plus or minus 0.002 in. from the standard size specified. The length shall not vary more than plus or minus $\frac{1}{4}$ in. from that specified.

(*b*) The coverings shall be concentric to the extent that the maximum core-plus-one-covering dimension shall not exceed the minimum core-plus-one-covering dimension by more than 5 per cent. The concentricity may be measured by any suitable means.

(*c*) Core wire and coverings shall be free of defects which would interfere with uniform performance of the electrodes.

Exposed Core

10. (*a*) The grip portion of the electrode shall be free from covering for approximately $\frac{3}{4}$ in. but not more than $1\frac{1}{4}$ in. for end-grip electrodes and approximately $1\frac{1}{2}$ in. but not more than 2 in. for center-grip electrodes.

(*b*) The arc end of each electrode shall be sufficiently bare to permit easy striking of the arc. The distance from the arc end to the first point where the full cross-section of the covering prevails shall not exceed the diameter of the core wire. However, for electrodes larger than $\frac{1}{8}$ in. the core wire shall not be exposed around more than one-half the circumference at a distance of $\frac{1}{8}$ in. or more from the arc end.

Standard Sizes and Lengths

11. Standard sizes and lengths of electrodes are as shown in the following table. In all cases, standard size refers to the diameter of the core wire.

Standard Sizes, Diameter of Core Wire, in.	Standard Lengths, in.
$\frac{1}{16}$, $\frac{5}{64}$, $\frac{3}{32}$	9 or 18[a]
$\frac{1}{8}$, $\frac{5}{32}$, $\frac{3}{16}$, $\frac{1}{4}$	14

[a] Center gripping of 18-in. length electrodes is standard. In all other cases, end gripping is standard.

Packaging for Domestic Use

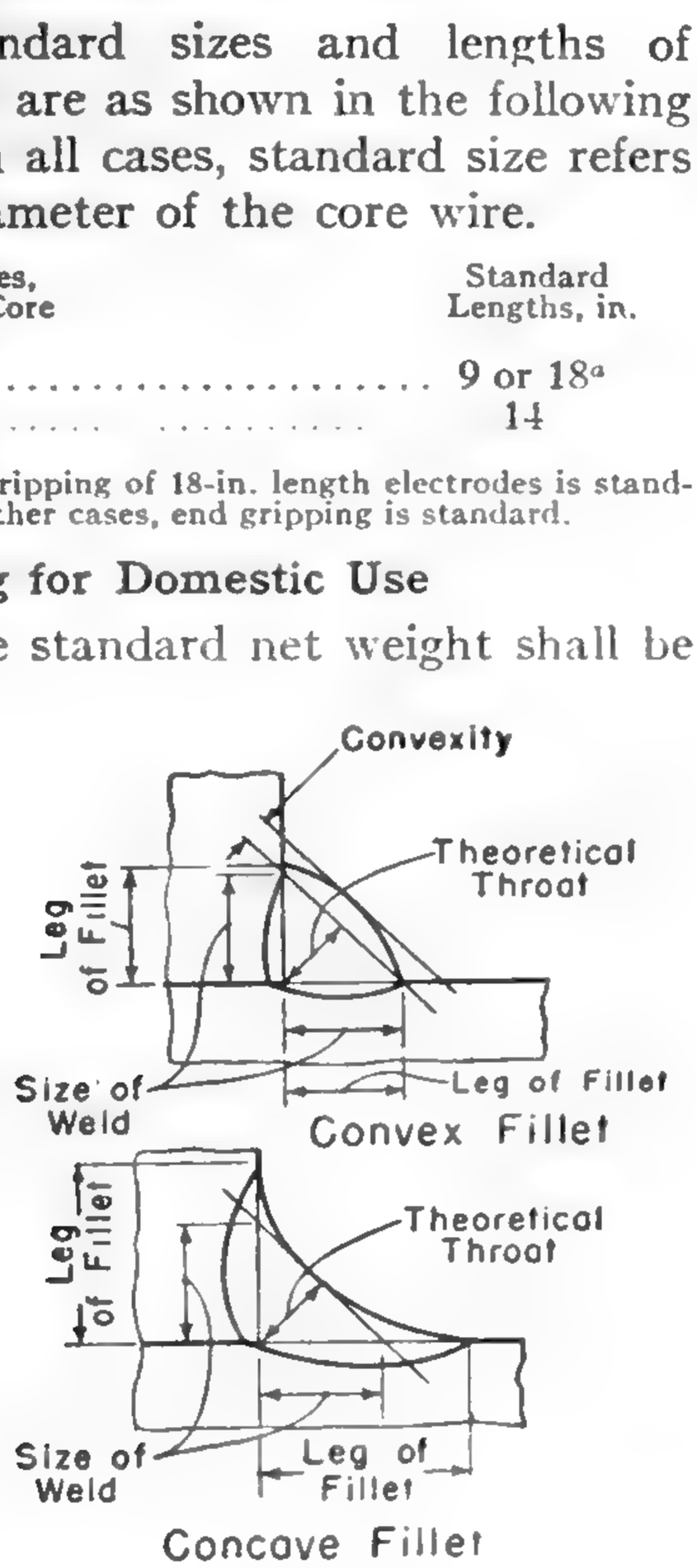
12. The standard net weight shall be 25 or 50 lb., packaged in a container which will insure against injury during shipment and against injury in storage when stored in a protected warehouse or its equivalent.

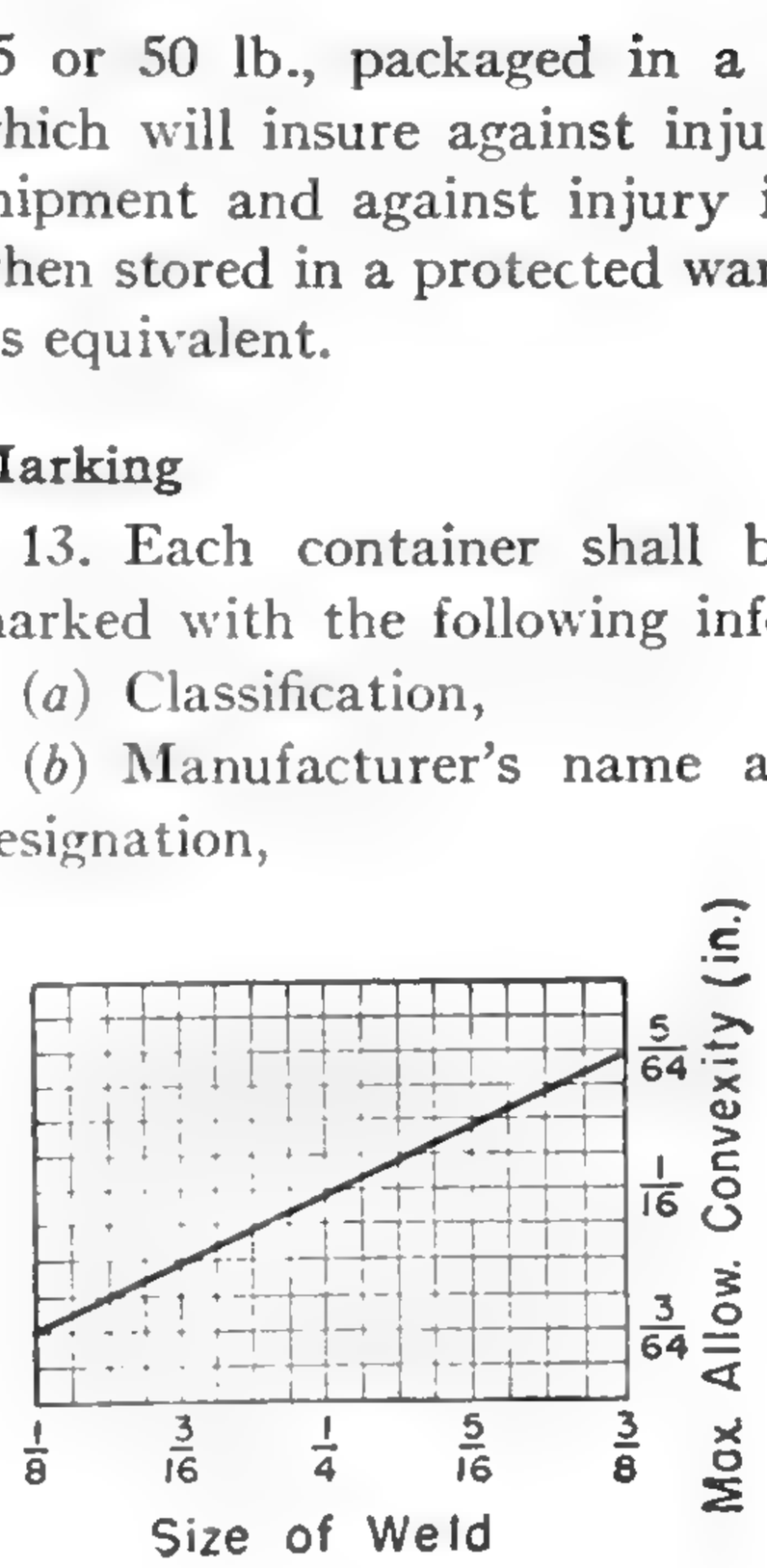
Marking

13. Each container shall be legibly marked with the following information:

(*a*) Classification,

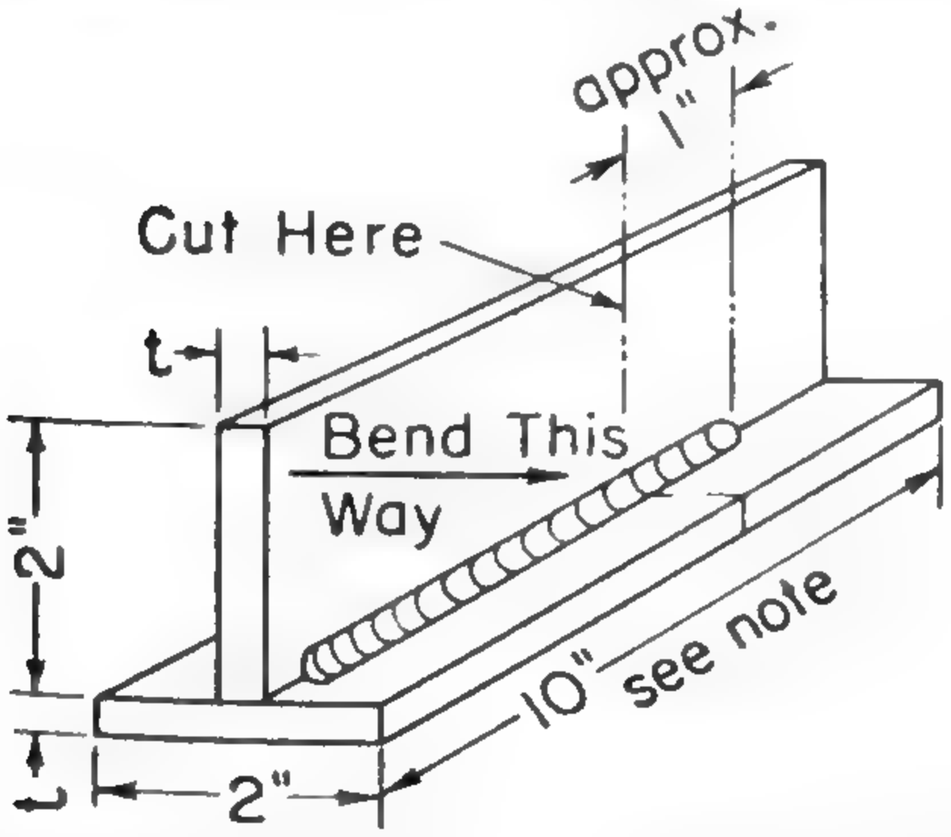
(*b*) Manufacturer's name and trade designation,





Dimensions of Fillet Welds.

NOTE 1.—Size of fillet weld = Leg length of largest inscribed isosceles right triangle.
NOTE 2.—Length of horizontal leg of fillet weld shall not vary more than 1/16 in. from length of vertical leg.
NOTE 3.—Fillet weld size, convexity and leg lengths of fillet welds shall be determined by actual measurement to nearest 1/64 in.) on a section laid out with scribed lines as shown.



Electrode Diameter, in.	Thickness of Plate, *t*, in.	Position of Welding	Required Fillet Size, max., in.
3/8	1/4	V	1/4
		H and OH	5/16
5/32	1/4	V	7/16
		H and OH	1/4
5/16	3/8	H	5/16
1/4	3/8	H	3/8

NOTE.—When testing 18-in. end grip electrodes, length shall be 15 in., min.

FIG. 2.—Fillet Weld Test.

(*c*) Standard size and net weight, and
(*d*) Guarantee.

Color Markings for Electrode Identification

14. The stub end (or bare portion of center-grip electrodes) shall be color marked to designate the grade as shown

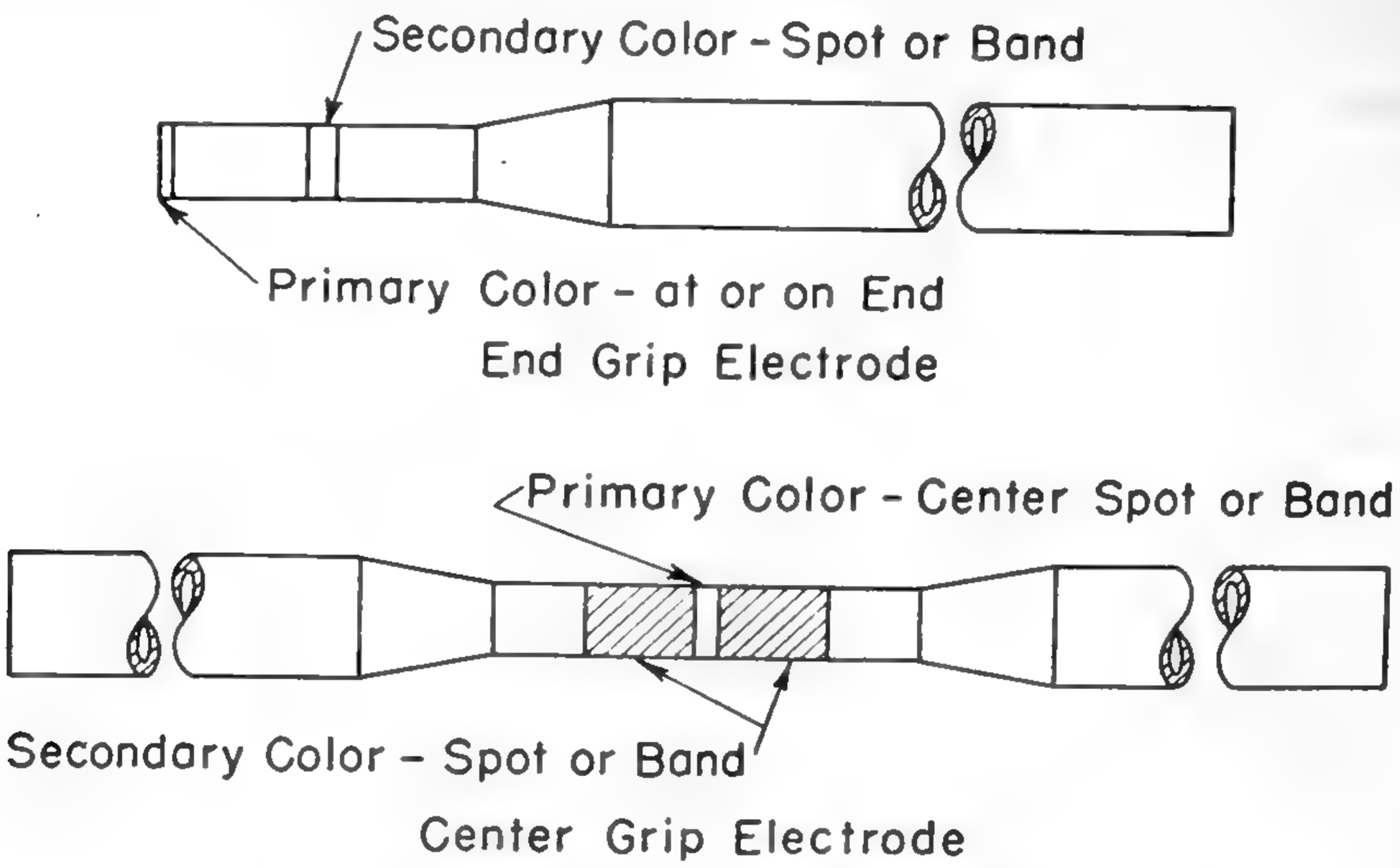


FIG. 3.—Color Marking for Electrode Identification.

in Fig. 3, using the colors specified in the following table:

Series	Color	
	End	Side
E308	yellow	none
E309	black	white
E310	red	none
E316	yellow	white
E317	yellow	brown
E330	green	none
E347	yellow	blue
E410	gray	brown
E430	gray	green
E502	gray	blue

Guarantee

15. The manufacturer shall guarantee that the electrodes in all sizes and classifications conform to these specifications and each container shall be so marked. The manufacturer's responsibility shall be limited to replacement of any electrodes which do not conform to the requirements of these specifications.

PART II.—DETAILS OF TESTS

Required Tests

16. The tests specified in Sections 4, 5, 6 and 7 shall be conducted in accordance with the requirements of Table III for each size and classification of electrodes using the positions of welding and types of current shown; all of the details of testing shall conform to the requirements of this Part II.

Material for Test Plates

17. (*a*) For the all-weld-metal tension test the steel to be used shall conform to the Standard Specifications for Low and Intermediate Tensile Strength Carbon-Steel Plates of Flange and Firebox Qualities (Plates 2 in. and Under in Thickness) (A.S.T.M. Designation: A 285).[3] The plates and backing shall be clad before

[3] 1947 Supplement to Book of A.S.T.M. Standards, Part I-A.

assembling with two layers of weld metal deposited (as shown in Fig. 4) by the electrodes being classified.

(*b*) For the fillet-weld test the steel to be used shall conform to the following specifications of the American Society for Testing Materials:

(*1*) For electrodes of the E308, E309, E310, E316, E317, E330, and E347 series of classification.—Standard Specifications for Corrosion-Resisting Chromium-Nickel Steel Plate, Sheet, and Strip (A.S.T.M. Designation: A 167),[4] grade 3, hot-rolled.

(2) For electrodes of the E410 and E430 series of classifications.—Standard Specifications for Corrosion-Resisting Chromium Steel Plate, Sheet, and Strip (A.S.T.M. Designation: A 176),[4] grade 4, hot-rolled.

(3) For electrodes of the E502 series of classifications.—Standard Specifications for Low and Intermediate Tensile Strength Carbon-Steel Plates of Flange and Firebox Qualities (Plates 2 in. and Under in Thickness) (A.S.T.M. Designation: A 285).[3]

[4] 1946 Book of A.S.T.M. Standards, Part I-A.

Electrode Size, in.	Test Plate Thickness, in.	Diameter of Tension Test Specimen, in.	Dimensions of Test Plate and Tension Test Specimen, in.								
	I	A	B	C	D	E	F	G	H	J	K
1/8	1/2	0.252 ± 0.005	1	3/8	2 1/2	1/2	3/16	1 1/4	3	1/4	3/16
5/32 to 1/4, incl.	3/4	0.500 ± 0.010	2	3/4	4 1/2	3/4	3/8	2 1/4	5	1/2	1/4

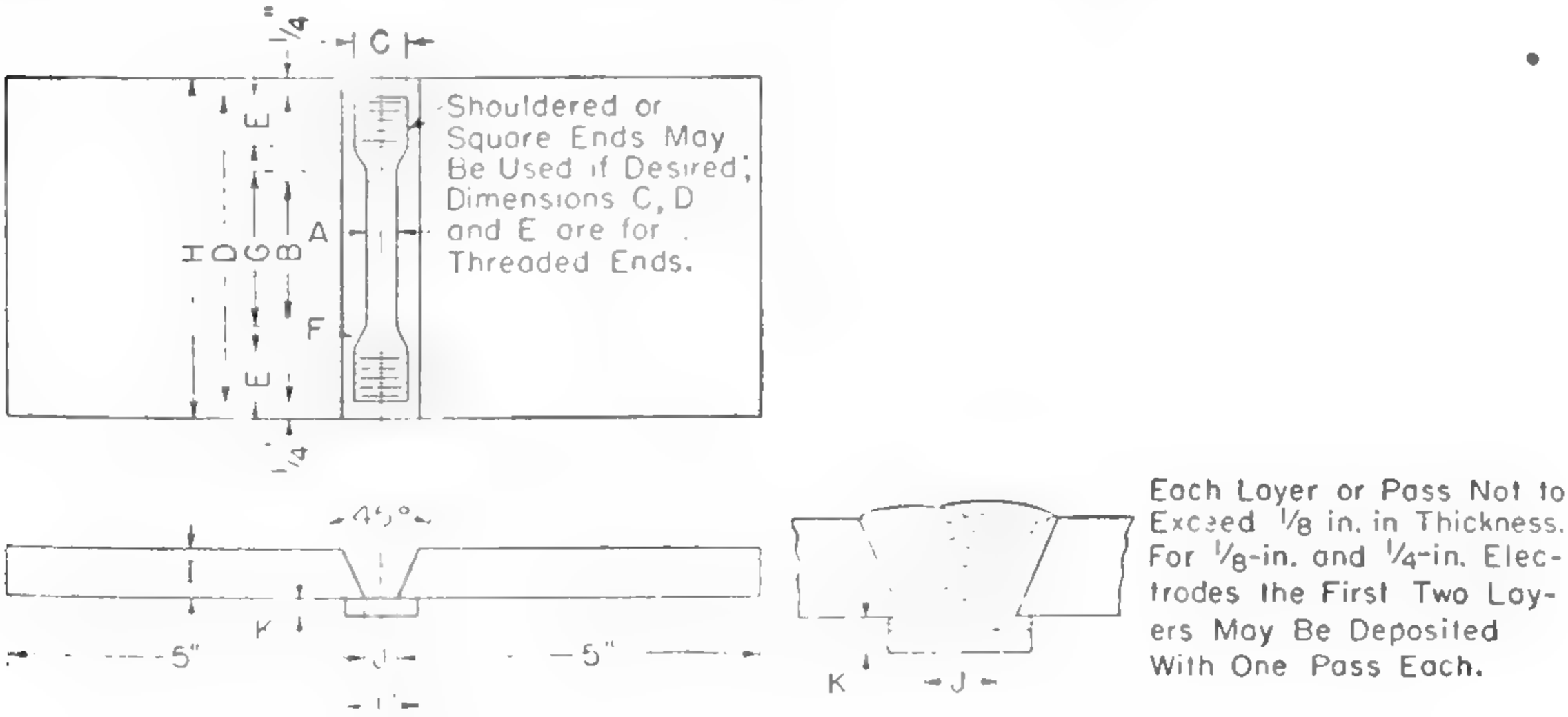


FIG. 4.—Requirements for Preparation of All-Weld-Metal Tension Test Specimens.

Chemical Analysis

18. (*a*) The required pads shall be deposited using the type of current prescribed in Table III excepting that where both a.c. and d.c. are specified, only one type of current need be used. Pads of weld metal for chemical analysis shall be prepared as prescribed in Paragraphs (*b*) and (*c*), and chemical analyses shall be made from samples machined from the pads in a manner prescribed in Paragraph (*d*).

(*b*) Weld pads shall be deposited on mild-steel base plates (carbon 0.25 per cent, max.) and shall conform to the following dimensions:

Electrode Size, in.	Pad Size, min., in.
$\frac{1}{16}$, $\frac{5}{64}$, $\frac{3}{32}$	1 by 1 by $\frac{1}{2}$
$\frac{1}{8}$, $\frac{5}{32}$, $\frac{3}{16}$	$1\frac{1}{2}$ by $1\frac{1}{2}$ by $\frac{1}{2}$
$\frac{1}{4}$	2 by 2 by $\frac{1}{2}$

(*c*) The pads shall be deposited in layers, each pass of which shall measure in width one and a half to two and a half times the diameter of the core wire. After each layer, the pad shall be immersed in water (temperature unimportant) for 30 sec. The arc length shall be as short as practicable, the average arc voltage not exceeding the following values; the average current shall be within the following ranges:

Electrode Diameter, in.	Arc Amperes	Arc Voltage
$\frac{1}{16}$	35 to 45	24
$\frac{5}{64}$	45 to 55	24
$\frac{3}{32}$	65 to 80	24
$\frac{1}{8}$	90 to 110	25
$\frac{5}{32}$	120 to 140	26
$\frac{3}{16}$	160 to 180	27
$\frac{1}{4}$	220 to 240	28

(*d*) The top surface of the pad shall be removed and discarded, and a 1-oz. sample for analysis shall be removed by machining, drilling, or milling in such a manner that no metal shall be removed within $\frac{1}{4}$ in. from the surface of the base plate. Machining shall be done with high-speed tools, and the use of lubricants shall be avoided.

NOTE.—Pads which are too hard for machining may be given an annealing heat treatment (see Table IV).

All-Weld-Metal Tension Test

19. (*a*) Tension tests shall be made as prescribed in Paragraphs (*b*) to (*e*), using the types of current (reversed polarity, if d.c.) for each size and classification of electrode as shown in Table III. The plates and backing shall be clad before assembling with two layers of weld metal, deposited by the electrodes being classified, as shown in Fig. 4.

(*b*) Plates shall be restrained during welding sufficiently to prevent warpage in excess of 5 deg. A test plate which has warped more than 5 deg. shall be discarded. (Test plates shall not be straightened.)

(*c*) The test assembly shall be within the following temperature ranges before starting to weld each pass:

Series	Interpass Temperature, deg. Fahr.	
	Minimum	Maximum
E308	60	300
E309	60	300
E310	60	300
E316	60	300
E317	60	300
E330	60	300
E347	60	300
E410	300	500
E430	300	500
E502	300	500

If after any pass the maximum temperature specified above is exceeded, plates shall be allowed to cool in air. (Do not cool in water.)

(*d*) One all-weld-metal tension test specimen shall be machined from each finished test assembly as shown in Fig. 4.

Fillet-Weld Test

20. (*a*) When a classification of electrode permits its use with more than one type of current (or polarity), it shall be tested using each type of current (and polarity).

(*b*) A fillet-welded tee-joint shall be prepared in accordance with Fig. 2 including the dimensions of test plates, positions of welding and size of fillet-weld prescribed therein for the particular size of electrode being tested.

(*c*) In preparing the two plates forming the test assembly, the standing member shall have one edge machined throughout its length so that when it is set upon the base plate, which shall be straight and smooth, there will be

intimate contact for the entire length of the joint.

(*d*) A single-pass fillet weld shall be deposited on one side of the joint using the types of current (and polarity if d.c.) prescribed in Table III. When welding in the vertical position is specified, the progression shall be upward. The first electrode used shall be consumed for its full length except for a stub end of not more than 2 in. Additional electrodes, if necessary, shall then be used to complete the weld for the full length of the joint, consuming each electrode completely as stated above—insofar as permitted by the length of the assembly.

(*e*) After completing the weld on the first side of the joint, the assembly shall be cooled to room temperature (but not less than 60 F.) by any convenient means (Note) before commencing to weld on the second side.

NOTE.—If water is used as the coolant, care should be taken to ascertain that it has been thoroughly removed from the joint.

(*f*) The fillet weld on the second side of the joint shall be deposited by the same procedure as was the first weld.

(*g*) At a point approximately 1 in. back from the crater end of the deposit made with the first electrode on the first side of the joint the specimen shall be cut. Either face may be polished and etched to permit examination.

(*h*) The polished and etched face shall be scribed as shown in Fig. 2 and the size, the leg lengths and the convexity (of convex fillets) shall be determined to the nearest $\frac{1}{64}$ in. by actual measurement.

AMERICAN WELDING SOCIETY
SPECIFICATION A 5.5–48T

E. Tentative Specifications for

LOW-ALLOY STEEL ARC-WELDING ELECTRODES[1]

A.S.T.M. Designation: A 316 – 48 T

ISSUED, 1948.[2]

These Tentative Specifications have been approved by the sponsoring committee and accepted by the Cooperating Societies in accordance with established procedures, for use pending adoption as standard. Suggestions for revisions should be addressed to the Headquarters of the A.S.T.M., 1916 Race St., Philadelphia 3, Pa., or of the A.W.S., 33 W. 39th St., New York 18, N. Y.

These specifications were prepared jointly by the American Welding Society and the American Society for Testing Materials.

Scope

1. These specifications cover covered metal arc-welding electrodes for the welding of low-alloy steels of weldable quality.

NOTE.—The requirements of these specifications pertain to the tensile strength and elongation of the deposited metal and not to high- or low-temperature characteristics, creep properties, or corrosion resistance.

PART I.—CLASSIFICATION AND ACCEPTANCE

Classification

2. (*a*) The electrodes are classified in Table I on the basis of the tensile strength of the deposited weld metal, type of covering, and type of current and welding positions of the electrodes.

(*b*) Any electrode classified under one classification shall not be classified under any other classification.

Manufacture

3. The electrodes may be made by any methods that will yield a product conforming to the requirements of these specifications.

Chemical Composition

4. The electrodes shall not be required to comply with any limitations on the chemistry of electrode or of deposited metal.

Physical Tests

5. (*a*) Physical tests, comprising (*1*) an all-weld-metal tension test to determine the mechanical properties of the deposited metal, and (*2*) fillet-weld tests to demonstrate the usability of an electrode as to welding position, soundness

[1] Under the standardization procedure of the two Societies, these specifications are under the jurisdiction of the A.W.S.-A.S.T.M. Joint Committee on Filler Metal.

[2] Accepted by the A.S.T.M. Administrative Committee on Standards, June 7, 1948; approved by the A.W.S. Board of Directors, May 17, 1948.

These specifications formerly comprised a portion of the Tentative Specifications for Iron and Steel Arc-Welding Electrodes (A 233 - 45 T), but were revised and separated from Specifications A 233 in 1948.

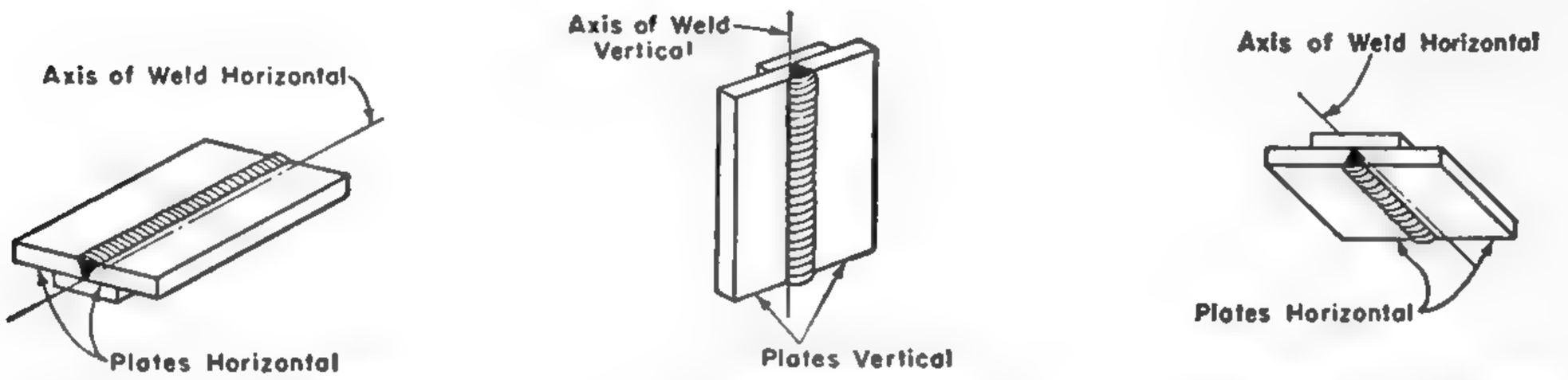
TABLE I.—ELECTRODE CLASSIFICATION.

Electrode Classification Number	Type of Covering	Capable of Producing Satisfactory Welds in Positions Shown[a]	Type of Current
E70 Series.—Minimum Tensile Strength of Deposited Metal in Stress-Relieved Condition 70,000 psi.			
E7010	High cellulose sodium	F, V, OH, H	For use with d.c., reversed polarity (electrode positive) only.
E7011	High cellulose potassium	F, V, OH, H	For use with a.c. or d.c., reversed polarity (electrode positive).
E7013	High titania potassium	F, V, OH, H	For use with a.c. or d.c., straight polarity (electrode negative).
E7015	Low hydrogen sodium	F, V, OH, H	For use with d.c., reversed polarity (electrode positive) only.
E7016	Low hydrogen potassium	F, V, OH, H	For use with a.c. or d.c., reversed polarity (electrode positive).
E7020	High iron oxide	H-Fillets, F	For use with d.c., straight polarity (electrode negative) or a.c. for horizontal fillet welds; and d.c., either polarity, or a.c. for flat-position welding.
E7025	Low hydrogen sodium	H-Fillets, F	For use with d.c., reversed polarity (electrode positive) only.
E7026	Low hydrogen potassium	H-Fillets, F	For use with a.c. or d.c., reversed polarity (electrode positive).
E7030	High iron oxide	F	For use with d.c., either polarity, or a.c.
E80 Series.—Minimum Tensile Strength of Deposited Metal in Stress-Relieved Condition 80,000 psi.			
E8010	High cellulose sodium	F, V, OH, H	For use with d.c., reversed polarity (electrode positive) only.
E8011	High cellulose potassium	F, V, OH, H	For use with a.c. or d.c., reversed polarity (electrode positive).
E8013	High titania potassium	F, V, OH, H	For use with a.c. or d.c., straight polarity (electrode negative).
E8015	Low hydrogen sodium	F, V, OH, H	For use with d.c., reversed polarity (electrode positive) only.
E8016	Low hydrogen potassium	F, V, OH, H	For use with a.c. or d.c., reversed polarity (electrode positive).
E8020	High iron oxide	H-Fillets, F	For use with d.c., straight polarity (electrode negative), or a.c. for horizontal fillet welds; and d.c., either polarity, or a.c. for flat-position welding.
E8025	Low hydrogen sodium	H-Fillets, F	For use with d.c., reversed polarity (electrode positive) only.
E8026	Low hydrogen potassium	H-Fillets, F	For use with a.c. or d.c., reversed polarity (electrode positive).
E8030	High iron oxide	F	For use with d.c., either polarity, or a.c.
E90 Series.—Minimum Tensile Strength of Deposited Metal in Stress-Relieved Condition 90,000 psi.			
E9010	High cellulose sodium	F V, OH, H	For use with d.c., reversed polarity (electrode positive) only.
E9011	High cellulose potassium	F, V, OH, H	For use with a.c. or d.c., reversed polarity (electrode positive).
E9013	High titania potassium	F, V, OH, H	For use with a.c. or d.c., straight polarity (electrode negative).
E9015	Low hydrogen sodium	F, V, OH, H	For use with d.c., reversed polarity (electrode positive) only.
E9016	Low hydrogen potassium	F, V, OH, H	For use with a.c. or d.c., reversed polarity (electrode positive).
E9020	High iron oxide	H-Fillets, F	For use with d.c., straight polarity (electrode negative), or a.c. for horizontal fillet welds; and d.c., either polarity, or a.c. for flat-position welding
E9025	Low hydrogen sodium	H-Fillets, F	For use with d.c., reversed polarity (electrode positive) only.
E9026	Low hydrogen potassium	H-Fillets, F	For use with a.c. or d.c., reversed polarity (electrode positive).
E9030	High iron oxide	F	For use with d.c., either polarity, or a.c.
E100 Series.—Minimum Tensile Strength of Deposited Metal in Stress-Relieved Condition 100,000 psi.			
E10010	High cellulose sodium	F, V, OH, H	For use with d.c., reversed polarity (electrode positive) only.
E10011	High cellulose potassium	F, V, OH, H	For use with a.c. or d.c., reversed polarity (electrode positive).
E10013	High titania potassium	F, V, OH, H	For use with a.c. or d.c., straight polarity (electrode negative).
E10015	Low hydrogen sodium	F, V, OH, H	For use with d.c., reversed polarity (electrode positive) only.

TABLE I.—ELECTRODE CLASSIFICATION—*Continued.*

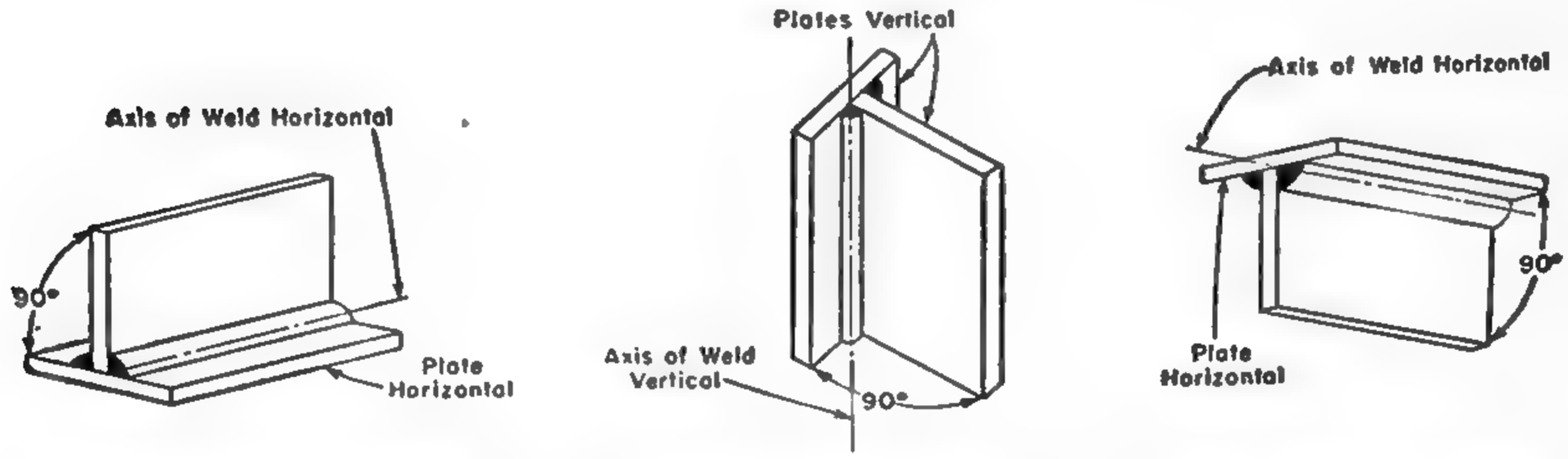
Electrode Classification Number	Type of Covering	Capable of Producing Satisfactory Welds in Positions Shown[a]	Type of Current
E100 Series.—Minimum Tensile Strength of Deposited Metal in Stress-Relieved Condition 100,000 psi.—*Continued.*			
E10016.....	Low hydrogen potassium	F, V, OH, H	For use with a.c. or d.c., reversed polarity (electrode positive).
E10020.....	High iron oxide	H-Fillets, F	For use with d.c., straight polarity (electrode negative), or a.c. for horizontal fillet welds; or a.c. for flat-position welding.
E10025.....	Low hydrogen sodium	H-Fillets, F	For use with d.c., reversed polarity (electrode positive) only.
E10026.....	Low hydrogen potassium	H-Fillets, F	For use with a.c. or d.c., reversed polarity (electrode positive).
E10030.....	High iron oxide	F	For use with d.c., either polarity, or a.c.

[a] The abbreviations F, H, V, OH and H-Fillets indicate welding positions (Figs. 1 and 2) as follows:
F = Flat
H = Horizontal
H-Fillets = Horizontal Fillets
V = Vertical } For electrodes 5/16 in. and under except in classifications
OH = Overhead } E*XX*15 and E*XX*16, 5/32 in. and under.



(*a*) Flat Groove Welds. (*b*) Vertical Groove Welds. (*c*) Overhead Groove Welds.

FIG 1.—Positions of Test Plates for Welding Guided-Bend Test Specimens.



(*a*) Horizontal Fillet Welds. (*b*) Vertical Fillet Welds (*c*) Overhead Fillet Welds.

FIG. 2.—Positions of Test Plates for Welding Fillet-Weld Test Specimens.

of weld metal and of fusion zone and weld contour, shall be performed at the place of manufacture of the electrodes, for the purpose of classification, when and as prescribed by the electrode manufacturer. For electrodes of the E70 series of classification the guided-bend test is prescribed in addition to the foregoing tests.

(*b*) At the option and expense of the purchaser any or all of the foregoing tests may be used as a basis for acceptance of electrodes. The guided-bend test, or fillet-weld test, or both,

TABLE II.—SUMMARY OF TESTS REQUIRED.[a]

Classification Number	Electrode: Diameter, in.	Electrode: Current and Polarity	All-Weld Metal Tension Test[b]	Guided-Bend Test[c]	Fillet-Weld Test[d]	Hydrogen Test[e]
E7010	1/16 to 1/8 incl.	d.c., reversed polarity (electrode positive)	not required	not required	not required	not required
	5/32 and 3/16		F	V and OH	V and OH	not required
	7/32		not required	not required	not required	not required
	1/4		F	F	H	not required
	5/16		F	F	not required	not required
E7011	1/16 to 1/8 incl.	a.c. and d.c. reversed polarity (electrode positive)	not required	not required	not required	not required
	5/32 and 3/16		F	V and OH	V and OH	not required
	7/32		not required	not required	not required	not required
	1/4		F	F	H	not required
	5/16		F	F	not required	not required
E7013	1/16 to 1/8 incl.	a.c. and d.c., straight polarity (electrode negative)	not required	not required	not required	not required
	5/32 and 3/16		F	V and OH	V and OH	not required
	7/32		not required	not required	not required	not required
	1/4		F	F	H	not required
	5/16		F	F	not required	not required
E7015	1/16 to 1/8 incl.	d.c., reversed polarity (electrode positive)	not required	not required	not required	not required
	5/32		F	V and OH	V and OH	not required
	3/16		F	F	H	F
	7/32		not required	not required	not required	not required
	1/4		F	F	H	not required
	5/16		F	F	not required	not required
E7016	1/16 to 1/8 incl.	a.c. and d.c., reversed polarity (electrode positive)	not required	not required	not required	not required
	5/32		F	V and OH	V and OH	not required
	3/16		F	F	H	F
	7/32		not required	not required	not required	not required
	1/4		F	F	H	not required
	5/16		F	F	not required	not required
E7020	1/16 to 1/8 incl.	d.c., straight polarity (electrode negative), and a.c. for horizontal fillet welds; d.c., both polarities, and a.c. for flat position welding	not required	not required	not required	not required
	5/32 and 3/16		F	F	H	not required
	7/32		not required	not required	not required	not required
	1/4		F	F	H	not required
	5/16		F	F	not required	not required
E7025	1/16 to 1/8 incl.	d.c., reversed polarity (electrode positive)	not required	not required	not required	not required
	5/32 and 3/16		F	F	H	F (3/16 in. only)
	7/32		not required	not required	not required	not required
	1/4		F	F	H	not required
	5/16		F	F	not required	not required
E7026	1/16 to 1/8 incl.	a.c. and d.c., reversed polarity (electrode positive)	not required	not required	not required	not required
	5/32 and 3/16		F	F	H	F (3/16 in. only)
	7/32		not required	not required	not required	not required
	1/4		F	F	H	not required
	5/16		F	F	not required	not required
E7030	1/16 to 1/8 incl.	d.c., both polarities, and a.c.	not required	not required	not required	not required
	5/32 and 3/16		F	F	not required	not required
	7/32		not required	not required	not required	not required
	1/4		F	F	not required	not required
	5/16		F	F	not required	not required
E8010 E9010 E10010	1/16 to 1/8 incl.	d.c., reversed polarity (electrode positive)	not required	not required	not required	not required
	5/32 and 3/16		F	not required	V and OH	not required
	7/32		not required	not required	not required	not required
	1/4		F	not required	H	not required
	5/16		F	not required	not required	not required
E8011 E9011 E10011	1/16 to 1/8 incl.	a.c. and d.c., reversed polarity (electrode positive)	not required	not required	not required	not required
	5/32 and 3/16		F	not required	V and OH	not required
	7/32		not required	not required	not required	not required
	1/4		F	not required	H	not required
	5/16		F	not required	not required	not required
E8013 E9013 E10013	1/16 to 1/8 incl.	a.c. and d.c., straight polarity (electrode negative)	not required	not required	not required	not required
	5/32 and 3/16		F	not required	V and OH	not required
	7/32		not required	not required	not required	not required
	1/4		F	not required	H	not required
	5/16		F	not required	not required	not required
E8015 E9015 E10015	1/16 to 1/8 incl.	d.c., reversed polarity (electrode positive)	not required	not required	not required	not required
	5/32		F	not required	V and OH	not required
	3/16		not required	not required	H	F
	7/32		F	not required	not required	not required
	1/4		F	not required	H	not required
	5/16		F	not required	not required	not required

TABLE II.—SUMMARY OF TESTS REQUIRED—*Continued*

Classification Number	Electrode: Diameter, in.	Electrode: Current and Polarity	All-Weld Metal Tension Test[b]	Guided-Bend Test[c]	Fillet-Weld Test[d]	Hydrogen Test[e]
E8016, E9016, E10016	1/16 to 1/8 incl.	a.c. and d.c., reversed polarity (electrode positive)	not required	not required	not required	not required
	5/32		F	not required	V and OH	not required
	3/16		F	not required	H	F
	7/32		not required	not required	not required	not required
	1/4		F	not required	H	not required
	5/16		F	not required	not required	not required
E8020, E9020, E10020	1/16 to 1/8 incl.	d.c., straight polarity (electrode negative), and a.c. for horizontal fillet welds; d.c., both polarities, and a.c. for flat-position welding	not required	not required	not required	not required
	5/32 and 3/16		F	not required	H	not required
	7/32		not required	not required	not required	not required
	1/4		F	not required	H	not required
	5/16		F	not required	not required	not required
E8025, E9025, E10025	1/16 to 1/8 incl.	d.c., reversed polarity (electrode positive)	not required	not required	not required	not required
	5/32 and 3/16		F	not required	H	F (3/16 in. only)
	7/32		not required	not required	not required	not required
	1/4		F	not required	H	not required
	5/16		F	not required	not required	not required
E8026, E9026, E10026	1/16 to 1/8 incl.	a.c. and d.c., reversed polarity (electrode positive)	not required	not required	not required	not required
	5/32 and 3/16		F	not required	H	F (3/16 in. only)
	7/32		not required	not required	not required	not required
	1/4		F	not required	H	not required
	5/16		F	not required	not required	not required
E8030, E9030, E10030	1/16 to 1/8 incl.	d.c., both polarities, and a.c.	not required	not required	not required	not required
	5/32 and 3/16		F	not required	not required	not required
	7/32		not required	not required	not required	not required
	1/4		F	not required	not required	not required
	5/16		F	not required	not required	not required

[a] For electrodes smaller than 5/32 in. and for the 7/32-in. size, the specified tests would require detailed modifications; such sizes may be judged from the results of tests on the 5/32- and 1/4-in. sizes, respectively.
[b] See Sections 7 and 19.
[c] See Sections 7 and 20.
[d] See Sections 7 and 21.
[e] See Sections 7 and 22.

are usually sufficient to determine acceptability.

Method of Test

6. Test specimens shall be prepared in kind and in number as specified in Table II and tests shall be conducted in accordance with Sections 17 to 22 of these specifications.

Test Requirements

7. In order to be classified under these specifications an electrode shall be capable of yielding the following results:

(*a*) The all-weld-metal tension test specimens after stress relieving shall conform to the requirements prescribed in Table III.

(*b*) Guided-bend test specimens, after bending, shall show no crack or other open defect exceeding $\frac{1}{8}$ in. measured in any direction. Cracks occurring on corners of a specimen during testing shall not be considered.

(*c*) The fillet-weld test specimen shall upon examination be free from cracks or other open defects affecting its strength. Upon examination of the face that has been polished and etched as prescribed, it is required that

(*1*) Each fillet weld shall have penetrated to or beyond the junction of the plate edges,

(*2*) Both legs of each fillet weld shall be of equal length within $\frac{1}{16}$ in.,

(*3*) The convexity (of convex fillet welds) shall be not more than $\frac{3}{64}$ in. for a $\frac{1}{8}$-in. fillet weld, plus $\frac{1}{64}$ in. additional for each additional $\frac{1}{8}$ in. of fillet weld size (See Fig. 10).

(*4*) The welds and the base metal shall be free from cracks, and

(*5*) The weld shall be reasonably free from undercutting, overlap, trapped slag and porosity.

(*d*) The amount of gas collected in the determination for hydrogen as specified in Section 22, shall not exceed an average of 0.1 cu. cm. per gram of deposited metal for the four specimens tested.

Retests

8. If any specimen fails, one additional test assembly shall be welded and tested in accordance with the requirements of Section 7.

TABLE III.—MINIMUM TENSILE STRENGTH AND DUCTILITY REQUIREMENTS FOR STRESS-RELIEVED ALL-WELD-METAL TENSION TEST SPECIMEN.[a]

Electrode Classification Number	Tensile Strength, min., psi.	Yield Point, min., psi.	Elongation in 2 in., min., per cent
E7010	70 000	57 000	22
E7011	70 000	57 000	22
E7013	70 000	57 000	18
E7015	70 000	57 000	22
E7016	70 000	57 000	22
E7020	70 000	57 000	25
E7025	70 000	57 000	25
E7026	70 000	57 000	25
E7030	70 000	57 000	25
E8010	80 000	67 000	19
E8011	80 000	67 000	19
E8013	80 000	67 000	16
E8015	80 000	67 000	19
E8016	80 000	67 000	19
E8020	80 000	67 000	22
E8025	80 000	67 000	22
E8026	80 000	67 000	22
E8030	80 000	67 000	22
E9010	90 000	77 000	17
E9011	90 000	77 000	17
E9013	90 000	77 000	14
E9015	90 000	77 000	17
E9016	90 000	77 000	17
E9020	90 000	77 000	20
E9025	90 000	77 000	20
E9026	90 000	77 000	20
E9030	90 000	77 000	20
E10010	100 000	87 000	16
E10011	100 000	87 000	16
E10013	100 000	87 000	13
E10015	100 000	87 000	16
E10016	100 000	87 000	16
E10020	100 000	87 000	18
E10025	100 000	87 000	18
E10026	100 000	87 000	18
E10030	100 000	87 000	18

[a] See Table II for sizes to be tested.

Insulation

9. The coverings shall have sufficient electrical resistance to effectively insulate against a difference of potential of 100 v., 60 cycles a.c.

NOTE.—This does not apply to coiled wire which is to be used for machine welding.

Core Wire and Coverings

10. (*a*) The diameter of the core wire shall not vary more than plus or minus 0.002 in. from the standard size specified. The length shall not vary more than plus or minus $\frac{1}{4}$ in. from that specified.

(*b*) The covering on covered electrodes of all sizes shall be concentric to the extent that the maximum core-plus-one-covering dimension shall not exceed the minimum core-plus-one-covering dimension by more than 3 per cent. The concentricity shall be measured by any suitable means.

(*c*) Core wire and coverings shall be free of defects which would interfere with uniform performance of the electrodes.

Exposed Core

11. (*a*) Covered electrodes for manual welding shall be bare or free from covering for a distance of about $\frac{3}{4}$ in., but not more than $1\frac{1}{4}$ in., for making contact with the holder.

(*b*) The arc end of each electrode shall be sufficiently bare to permit easy striking of the arc. The distance from the arc end to the first point where the full cross-section of the covering prevails shall not exceed the diameter of the core wire. However, for electrodes larger than $\frac{1}{8}$ in. the core wire shall not be exposed around more than one-half the circumference at a distance of $\frac{1}{8}$ in. or more from the arc end.

Standard Sizes and Lengths

12. Standard sizes and lengths of electrodes are as shown in the following table. In all cases, standard size refers to the diameter of the core wire.

Standard Sizes Diameter of Core Wire in.	Standard Lengths, in.[a]
$\frac{1}{16}$	9 or 18[b]
$\frac{5}{64}$ and $\frac{3}{32}$	12 or 18[b]
$\frac{1}{8}$ and $\frac{5}{32}$	14
$\frac{3}{16}$	14 or 18
$\frac{7}{32}$, $\frac{1}{4}$, $\frac{5}{16}$ and $\frac{3}{8}$	18

[a] Electrodes may also be provided in coils or reels.

[b] In the case of 18-in. lengths of $\frac{1}{16}$, $\frac{5}{64}$ and $\frac{3}{32}$-in. electrodes, center gripping of the electrodes is standard. In all other cases, end gripping is standard.

Packaging

13. Electrodes shall be packaged as follows:

(*a*) Bundles or boxes, not exceeding 50 lb. net weight, or

(*b*) Coils or reels, not exceeding approximately 200 lb. net weight.

Marking

14. All bundles, boxes, coils, or reels shall be legibly marked with the following information:

(*a*) Classification,

(*b*) Manufacturer's name and trade designation,

(*c*) Size and net weight, and

(*d*) Guarantee.

Color Markings for Electrode Identification

15. All electrodes shall be color marked in accordance with the current "Standard for Color Markings for Electrode Identification" of the National Electrical Manufacturers Association.

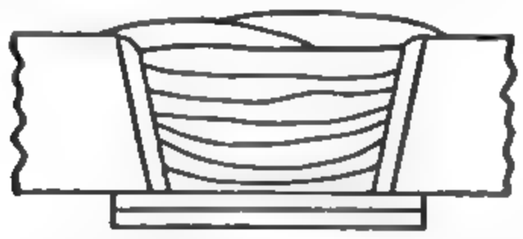
Guarantee

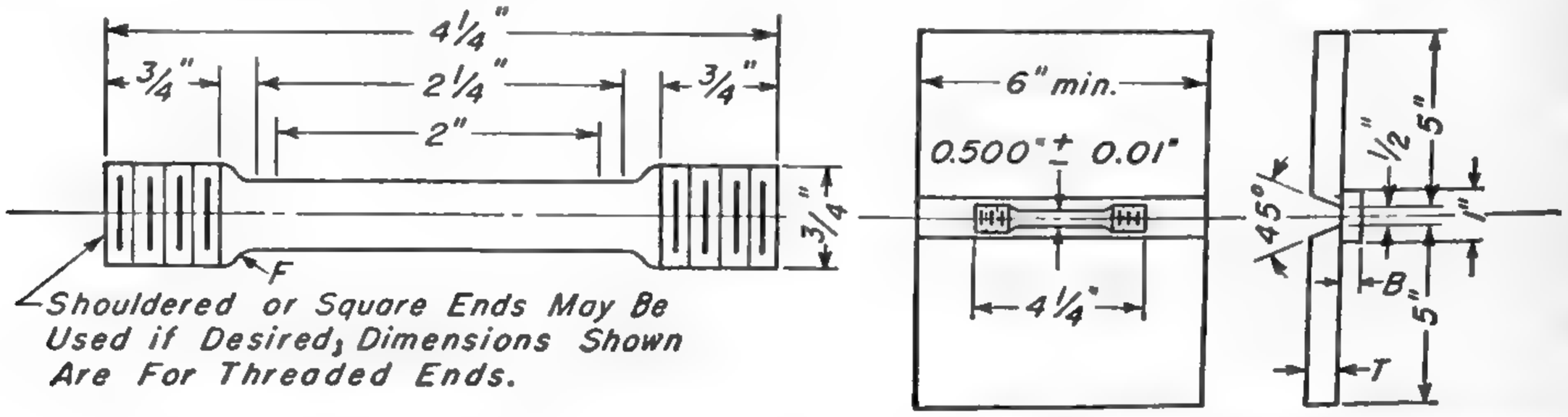
16. The manufacturer shall guarantee that the electrodes in all sizes and classifications conform to these specifications and each container shall be so marked. The manufacturer's responsibility shall be limited to replacement of any electrodes which do not conform to the requirements of these specifications.

PART II.—DETAILS OF TESTS

Required Tests

17. The tests specified in Sections 5, 6 and 7 shall be conducted in accordance with the requirements of Table II for each size and classification of electrodes using the positions of welding and types of current shown; all of the details of testing shall conform to the requirements of this Part II.

Type of Layers for Testing Electrodes	Electrode Size, in.	Test Plate Thickness, *T*, in.	Backing, *B*, in.
			
Edges of plate to be clad with deposited metal before depositing layers in groove, as shown. Each layer or pass not to exceed 1/8 in in thickness.	5/32	3/4	1/4
	3/16	3/4	1/4
	1/4	1	1/2
	5/16	1 1/4	1/2



Tension Test Specimen

Test Plate Showing Location of Test Specimen

FIG. 3.—Requirements for Preparation of All-Weld-Metal Tension Test Specimens.

Material for Test Plates

18. Steel to be used for test plates shall conform to one of the following specifications of the American Society for Testing Materials:

(*a*) Standard Specifications for Low and Intermediate Tensile Strength Car-

bon-Steel Plates of Flange and Firebox Qualities (Plates 2 in. and Under in Thickness) Grade C, (A.S.T.M. Designation: A 285),[3] or

(*b*) Standard Specifications for Steel for Bridges and Buildings (A.S.T.M. Designation: A 7),[4] open-hearth or electric-furnace steel.

All-Weld-Metal Tension Test

19. (*a*) For electrodes $\frac{5}{32}$ in. and larger a test plate as required by Table II shall be prepared as shown in Fig. 3. The sides of the welding groove and the top of the backing shall be clad with one layer of weld metal from an electrode of the same analysis as that being tested before depositing the first pass of the weld. The plate shall be insulated from the welding bench by $\frac{1}{2}$ in. of asbestos during welding. After the joint has been tacked, the assembly shall be heated in boiling water for approximately 5 min. prior to welding. The work shall be done in the flat position and in an ambient temperature of not less than 60 F. Weaving shall be the full width of the groove except for the last layer which shall be deposited in two passes.

(*b*) In testing electrodes of the E70 series of classifications, after depositing each pass, the assembly shall be left on the asbestos to cool in still air for a minimum of 5 min. and then immersed in boiling water for approximately 5 min. Each subsequent pass shall be deposited immediately after removal from boiling water. After the last pass, the assembly shall be removed from boiling water after the 5-min. period.

(*c*) In testing electrodes of the E80, E90 and E100 series of classifications, after depositing each pass, the assembly shall be left on the asbestos to cool in still air to a temperature below 212 F. before immersing it in boiling water for 5 min. Each subsequent pass shall be deposited immediately after removal from boiling water. After the last pass, the assembly shall be removed from the boiling water after the 5-min. period.

NOTE.—This immersion should not quench the assembly—the boiling water is intended simply as a preheat.

(*d*) If it is necessary to interrupt the pass sequence prescribed in Paragraphs (*b*) and (*c*) the assembly shall be removed from the boiling water after a 5-min. period and allowed to cool in still air at room temperature. When ready to resume work, the assembly shall be preheated in boiling water for a period of 5 min.

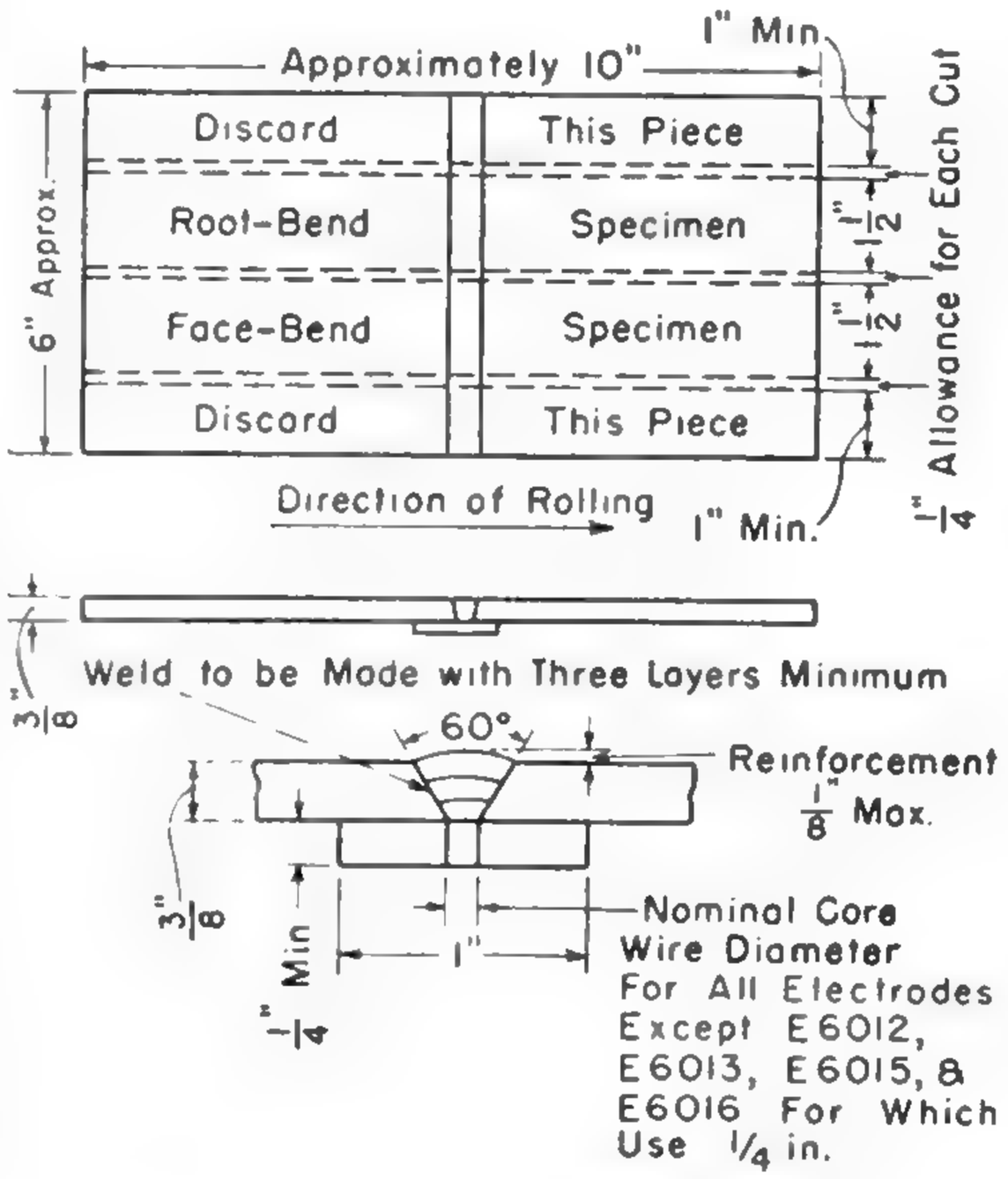


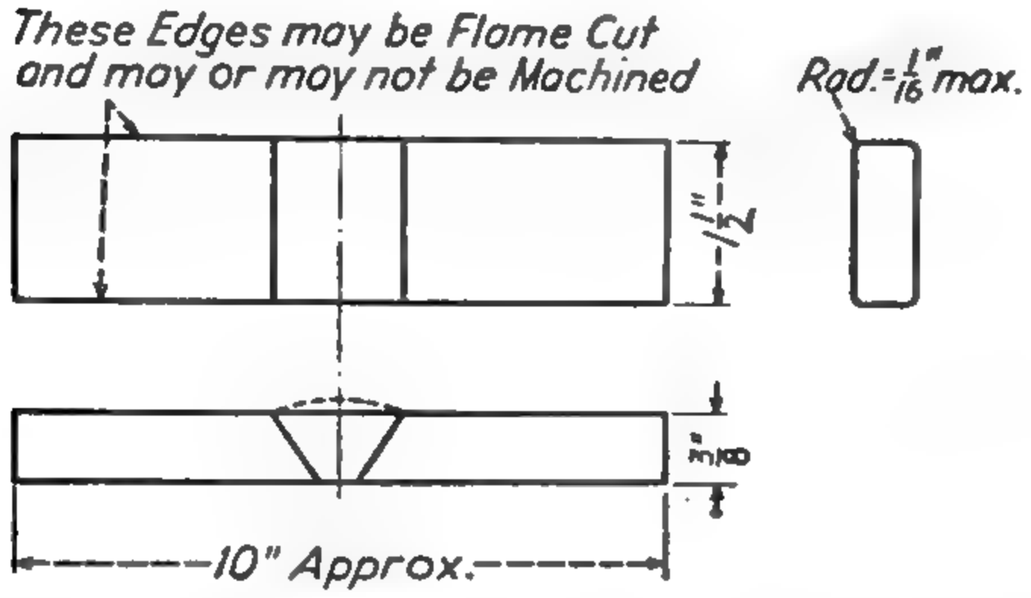
FIG. 4.—Test Joint for Guided-Bend Test.

(*e*) Specimens shall be stress relieved at a temperature of 1150 ± 25 F. for 1 hr. per in. of thickness. The temperature of the specimens shall be raised, in a suitable furnace, at the rate of 300 to 350 F. per hr. until a temperature of 1150 ± 25 F. has been attained. After this temperature has been reached, it shall be maintained for 1 hr. for each inch of the

[3] 1947 Supplement to Book of A.S.T.M. Standards, Part I-A.

[4] 1946 Book of A.S.T.M. Standards, Part I-A.

maximum thickness of the section, or fraction thereof. The specimens shall be cooled at the same rate specified for



NOTE.—Weld reinforcement and backing strip shall be removed flush with the surface of the specimen. Machining or grinding shall be done lengthwise on the specimen. The surface of the specimen to be tested shall be finely machined or ground.

FIG. 5.—Face- and Root-Bend Test Specimens.

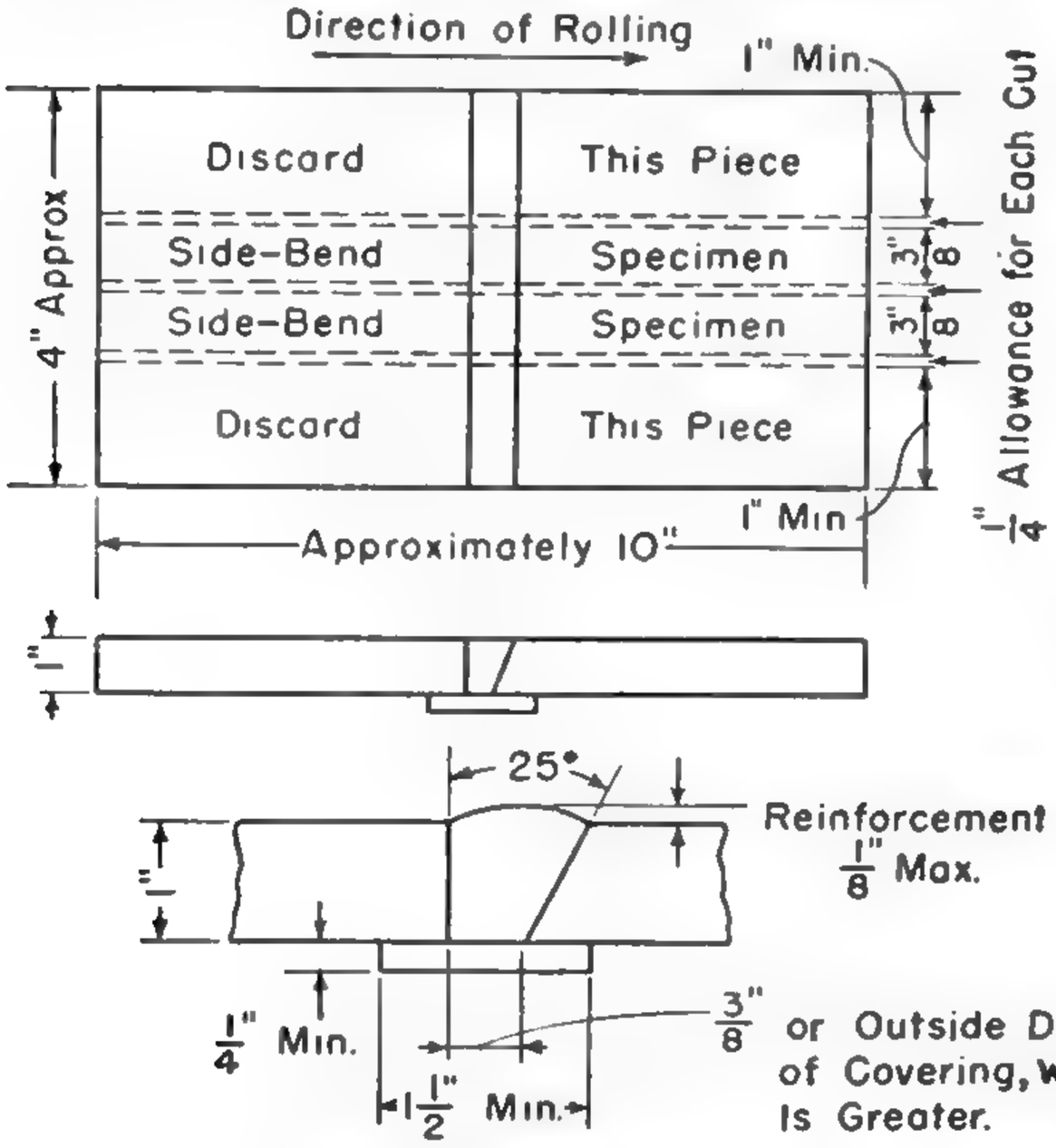


FIG. 6.—Test Joint for Side-Bend Test.

classifications only. When a classification of electrode permits its use with more than one type of current (or polarity), it shall be tested using each type of current (and polarity). The required test plates shall be so restrained or preset that warping due to welding will not

NOTE.—Specimens shall be sawed or machined from test joint. Weld reinforcement and backing strip shall be removed flush with the surface of the specimen. Machining or grinding shall be done lengthwise on the specimen. The surface of the specimen to be tested shall be finely machined or ground.

FIG. 7.—Side-Bend Specimen.

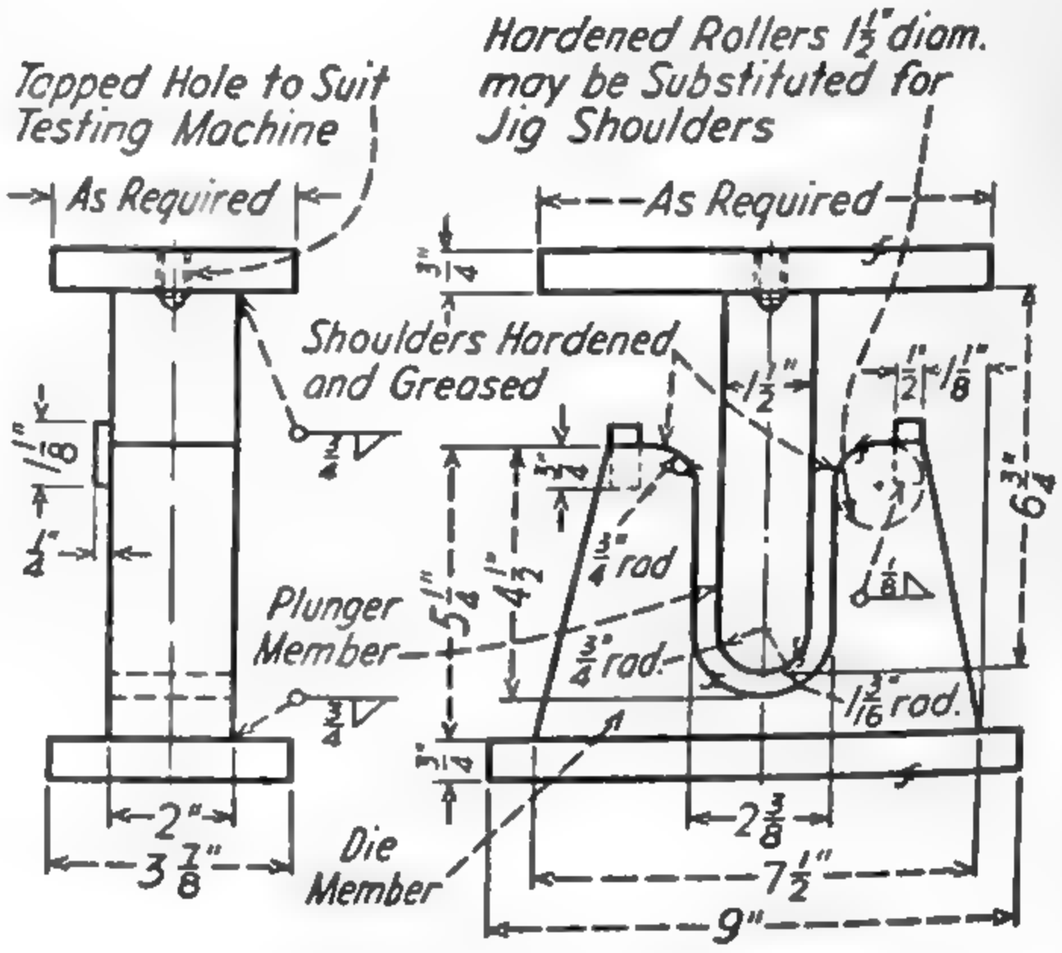


FIG. 8.—Guided-Bend Test Jig.

heating and may be removed from the furnace when the temperature of the plates has reached 600 F.

(*f*) One all-weld-metal tension test specimen shall be machined after removal from finished test assembly as shown in Fig. 3.

Guided-Bend Test

20. (*a*) The guided-bend test shall be required for electrodes of the E70 series of

cause the finished test plate to be out of line by more than 5 deg.

(*b*) For electrodes $\frac{5}{32}$ and $\frac{3}{16}$ in. in diameter a test joint conforming to the requirements of Fig. 4 shall be prepared in the welding positions and using the types of current (and polarity if d.c.) shown in Table II. The first pass shall be started with the test assembly at a temperature between 60 and 100 F. No stress-relieving shall be performed on the test assembly nor on the specimens re-

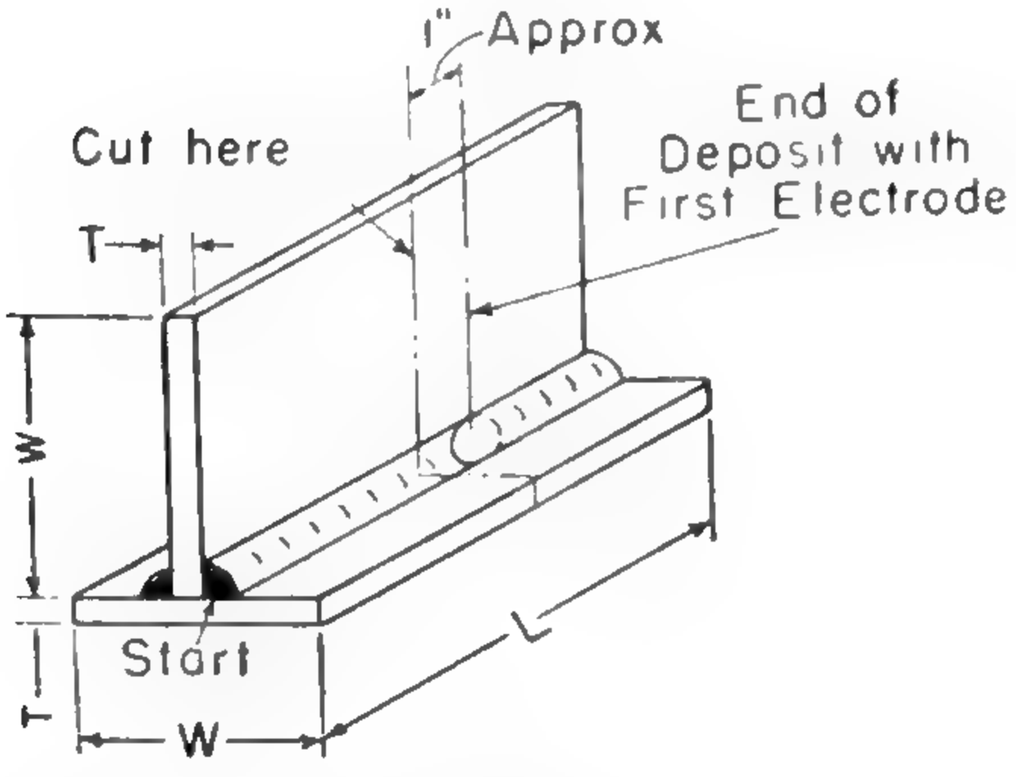
moved therefrom. From each completed test assembly one face-bend and one root-bend specimen shall be removed as shown in Fig. 4 and prepared for testing as shown in Fig. 5.

(*c*) For electrodes $\frac{1}{4}$ and $\frac{5}{16}$ in. in diameter, a test joint conforming to the requirements of Fig. 6 shall be prepared in the flat position using the types of current (and polarity if d.c.) shown in Table II. The first pass shall be started with the test assembly at a temperature between 60 and 100 F. No stress-relieving shall be performed on the test assembly nor on the specimens removed therefrom. From each completed test assembly two side-bend specimens shall be removed as shown in Fig. 6 and prepared for testing as shown in Fig. 7.

TABLE IV.—REQUIREMENTS FOR PREPARATION OF FILLET-WELD TEST ASSEMBLIES.

Electrode Classification Number	Diameter, in.	Plate Size, in.[a]			Position of Welding	Size of Fillet, in.
		Thickness, *T*	Width, *W*	Length, *L*		
E7010, E7011, E8010, E8011, E9010, E9011, E10010, E10011	$\frac{1}{16}$ to $\frac{3}{8}$ incl.	not required				
	$\frac{5}{32}$	$\frac{1}{4}$	3	12	V and OH	$\frac{5}{16}$ max.
	$\frac{3}{16}$	$\frac{3}{8}$	3	18	V and OH	$\frac{1}{4}$ max.
	$\frac{7}{32}$	not required				
	$\frac{1}{4}$	$\frac{1}{2}$	3	18	H	$\frac{1}{4}$ min.
	$\frac{5}{16}$	not required				
E7013, E8013, E9013, E10013	$\frac{1}{16}$ to $\frac{3}{8}$ incl.	not required				
	$\frac{5}{32}$	$\frac{1}{4}$	3	12	V and OH	$\frac{1}{4}$ max.
	$\frac{3}{16}$	$\frac{3}{8}$	3	18	V and OH	$\frac{5}{16}$ max.
	$\frac{7}{32}$	not required				
	$\frac{1}{4}$	$\frac{1}{2}$	3	18	H	$\frac{5}{16}$ min.
	$\frac{5}{16}$	not required				
E7015, E7016, E8015, E8016, E9015, E9016, E10015, E10016	$\frac{1}{16}$ to $\frac{3}{8}$ incl.	not required				
	$\frac{5}{32}$	$\frac{1}{4}$	3	12	V and OH	$\frac{1}{4}$ max.
	$\frac{3}{16}$	$\frac{3}{8}$	3	18	H	$\frac{5}{16}$ min.
	$\frac{7}{32}$	not required				
	$\frac{1}{4}$	$\frac{1}{2}$	3	18	H	$\frac{5}{16}$ min.
	$\frac{5}{16}$	not required				
E7020, E7025, E7026, E8020, E8025, E8026, E9020, E9025, E9026, E10020, E10025, E10026	$\frac{1}{16}$ to $\frac{1}{8}$ incl.	not required				
	$\frac{5}{32}$	$\frac{3}{8}$	3	18	H	$\frac{5}{32}$ min.
	$\frac{3}{16}$	$\frac{3}{8}$	3	18	H	$\frac{5}{16}$ min
	$\frac{7}{32}$	not required				
	$\frac{1}{4}$	$\frac{1}{2}$	3	18	H	$\frac{5}{16}$ min.
	$\frac{5}{16}$	not required				
E7030, E8030, E9030, E10030	not required					

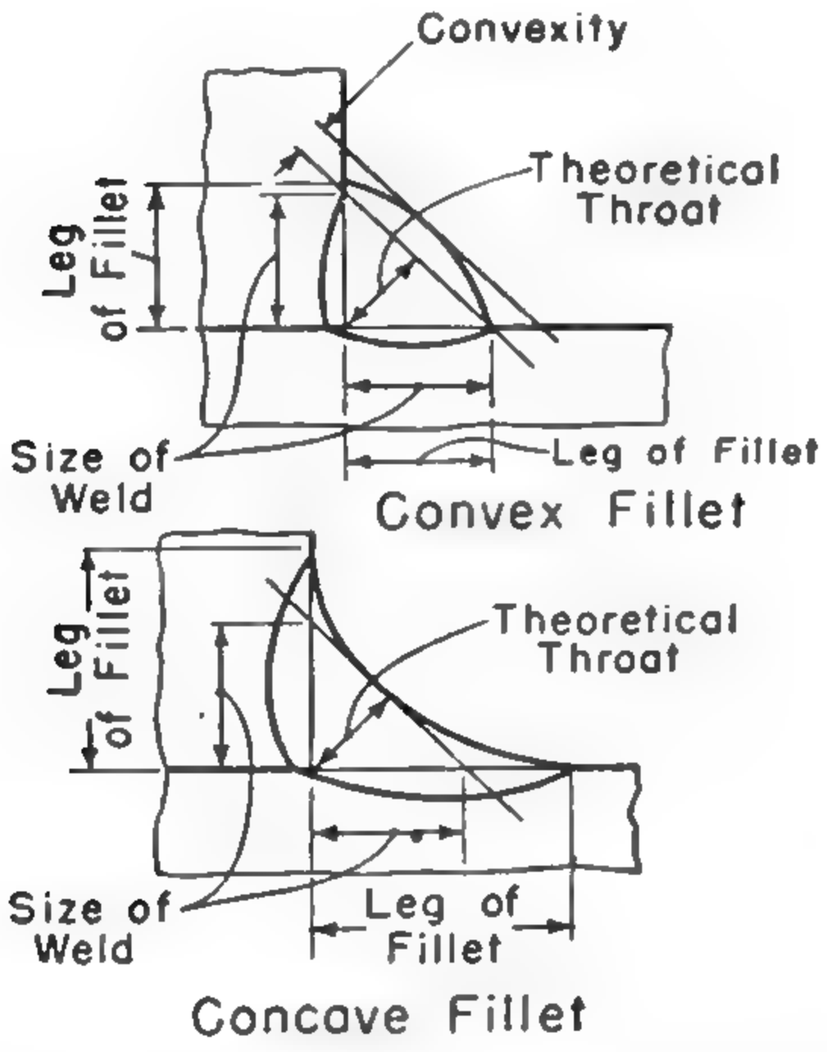
[a] See Fig. 9.



NOTE.—See Table IV for values of *T*, *W*, and *L*.

FIG. 9.—Preparation of Fillet-Weld Test Specimen.

(*d*) Each of the face-, root- and side-bend specimens shall be bent in a jig having the working contour shown in Fig. 8, and otherwise substantially in accordance with Fig. 8. Any convenient means may be used for moving the plunger member with relation to the die member. The specimen shall be placed on the die member with the weld at mid-span. Face-bend specimens shall be placed with the face of the weld directed



NOTE.—Size of fillet weld = Leg length of largest inscribed isosceles right triangle. Fillet weld size, convexity and leg lengths of fillet welds shall be determined by actual measurement (to nearest $\frac{1}{64}$ in. on a section laid out with scribed lines as shown.

FIG. 10.—Dimensions of Fillet Welds.

toward the gap; root-bend specimens shall be placed with the root of the weld directed toward the gap; side-bend specimens shall be placed with that side showing the greater defects, if any, directed toward the gap. The two members of the jig shall be forced together until the specimen conforms to a U-shape, and until a wire $\frac{1}{32}$ in. in diameter cannot be placed between the specimen and any point on the curvature of the plunger member of the jig. The specimen shall then be removed from the jig, and the convex surface examined.

Fillet-Weld Test

21. (*a*) When a classification of electrode permits its use with more than one type of current (or polarity), it shall be tested using each type of current (and polarity).

(*b*) A fillet-welded tee-joint assembly as shown in Fig. 9 shall be prepared. The dimensions of the test plates, positions of welding, and sizes of fillet shall be as prescribed in Table IV for the particular size and classification of the electrode being tested.

(*c*) In preparing the two plates forming the test assembly, the standing member shall have one edge machined throughout its length so that when it is set upon the base plate, which shall be straight and smooth, there will be intimate contact with the entire length of the joint.

(*d*) A single-pass fillet weld shall be deposited on one side of the joint using the types of current (and polarity if d.c.) prescribed in Table II. When welding in the vertical position is specified, the progression shall be upward. The first electrode used shall be consumed for its full length except for a stub end of not more than 2 in. Additional electrodes, if necessary, shall then be used to complete the weld for the full length of the joint, consuming each electrode completely as stated above—insofar as permitted by the length of the assembly.

(*e*) After completing the weld on the first side of the joint, the assembly shall be cooled to room temperature (but not less than 60 F.) by any convenient means (Note) before commencing to weld on the second side.

NOTE.—If water is used as the coolant, care should be taken to ascertain that it has been thoroughly removed from the joint.

(*f*) The fillet weld on the second side of the joint shall be deposited by the same procedure as was the first weld.

(*g*) At a point approximately 1 in.

back from the crater end of the deposit made with the first electrode on the first side of the joint the specimen shall be cut. Either face may be polished and etched to permit examination.

(*h*) The polished and etched face shall be scribed as shown in Fig. 10 and the size, the leg lengths and the convexity (of convex fillets) shall be determined to the nearest $\frac{1}{64}$ in. by actual measurement.

Hydrogen Test

22. (*a*) Four test specimens shall be prepared by depositing a single bead of weld metal on each of four plates measuring $\frac{1}{2}$ by 1 by approximately 5 in. in length using $\frac{3}{16}$-in. diameter electrodes. The type of current (and polarity) given in Table II shall apply using a current of 170 to 200 amp. and an arc voltage of 22 to 28 volts. The steel used for the test plates shall conform to one of those listed in Section 18. Before welding, the plates shall be thoroughly cleaned and weighed to the nearest 0.1 g.

(*b*) Not more than 1 in. of each electrode shall be burned off on a starting plate immediately prior to depositing weld metal on the test specimen. The weld bead shall be approximately $4\frac{1}{2}$ in. in length, and shall be made by consuming about 5 in. of electrode.

(*c*) Within 30 sec. of completion of welding of each specimen it shall be quenched in water at approximately 70 F. Within 120 sec. of completion of welding, each specimen shall have been cooled, cleaned and placed in an apparatus suitable for collecting hydrogen by displacement of glycerine. All four specimens shall be welded and placed in the hydrogen collecting apparatus within 30 min.

(*d*) The specimens shall be kept immersed in the glycerine for a period of 48 hr., the glycerine being maintained at a temperature of approximately 45 C. (113 F.).

(*e*) The specimens, after removal from the glycerine, shall be washed, dried and weighed to the nearest 0.1 g., to determine the amount of weld deposited. The amount of gas evolved shall be determined in terms of cubic centimeters per gram of weld metal.

AMERICAN WELDING SOCIETY
SPECIFICATION A5.6-48T

F. Tentative Specifications for
COPPER AND COPPER-ALLOY METAL ARC-WELDING ELECTRODES[1]

A.S.T.M. Designation: B 225 – 48 T

ISSUED, 1948.[2]

These Tentative Specifications have been approved by the sponsoring committee and accepted by the Cooperating Societies in accordance with established procedures, for use pending adoption as standard. Suggestions for revisions should be addressed to the Headquarters of the A.S.T.M., 1916 Race St., Philadelphia 3, Pa., or of the A.W.S., 33 W. 39th St., New York 18, N. Y.

These specifications were prepared jointly by the American Welding Society and the American Society for Testing Materials.

Scope

1. These specifications cover metal arc-welding electrodes for welding copper and copper alloys.

PART I.—CLASSIFICATION AND ACCEPTANCE

Classification

2. The electrodes are classified on the basis of mechanical properties and chemical analysis of the deposited weld metal as determined by the tests prescribed in these specifications.

Manufacture

3. The electrodes may be made by any method that will yield a product conforming to the requirements of these specifications.

Chemical Composition

4. The weld metal deposited by an electrode in accordance with the procedure prescribed in Section 18 shall conform to the chemical composition prescribed in Table I.

Physical Tests

5. (*a*) When and as prescribed by the electrode manufacturer, physical tests as follows shall be performed at the place of manufacture of the electrodes, for the purpose of classification:

(*1*) An all-weld-metal tension test to determine the mechanical properties of the deposited metal,

(*2*) A hardness test to determine the suitability of electrodes for producing surfaces of proper hardness, and

(*3*) A guided-bend test to demonstrate the usability of an electrode as to the soundness of weld metal and fusion zone and proper weld contour.

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[1] Under the standardization procedure of the two Societies, these specifications are under the jurisdiction of the A.W.S.-A.S.T.M. Joint Committee on Filler Metal.

[2] Accepted by the A.S.T.M. Administrative Committee on Standards, August 3, 1948; approved by the A.W.S. Board of Directors, June 23, 1948.

(*b*) At the option and expense of the purchaser any or all of the foregoing tests may be used as a basis for acceptance of electrodes. The guided-bend test is usually sufficient to determine acceptability.

Methods of Test

6. Test specimens shall be prepared in kind and in number as specified in Sections 18 to 20 and Table II.

Test Requirements

7. In order to be classified under these specifications an electrode shall be capable of yielding the following results:

(*1*) The mechanical properties of the all-weld-metal tension test specimens shall conform to the requirements prescribed in Table III,

(*2*) The average hardness of the pad shall conform to the requirements prescribed in Table III, and

(*3*) Guided-bend test specimens, after bending, shall show no crack or other open defect exceeding $\frac{1}{8}$ in. measured in any direction. Cracks occurring on

TABLE I.—CHEMICAL REQUIREMENTS.

NOTE.—Analysis shall be made for the elements for which specific values are shown in this table. If however, the presence of other elements is indicated in the course of routine analysis, further analysis shall be made to determine that the total of these other elements is not present in excess of the limits specified for "total impurities" in the last item in the table.

Element, per cent	Electrode Classification: E Cu (Copper)	E CuSn (Phosphor Bronze) A	E CuSn (Phosphor Bronze) C	E CuNi (Copper-Nickel)	E CuSi (Copper-Silicon)	E CuAl (Aluminum Bronze) A	E CuAl (Aluminum Bronze) B	E CuAl (Aluminum Bronze) C	E CuAl (Aluminum Bronze) D	E CuAl (Aluminum Bronze) E
Tin	not specified	4.0 to 6.0	7.0 to 9.0	*	not specified	*	*	*	*	*
Silicon	not specified	*	*	*	2.5 to 3.75	0.55 max.	0.55 max.	0.55 max.	0.55 max.	0.55 max.
Manganese	not specified	*	*	*	not specified	*	*	*	*	*
Iron	*	*	*	*	not specified	1.5 max.	3.0 to 5.0	3.0 to 5.0	3.0 to 5.0	3.0 to 5.0
Nickel	*	*	*	29.0 min.	not specified	0.5 max.	0.5 max.	0.5 max.	0.5 max.	0.5 max.
Aluminum	*	*	*	*	*	7.5 to 9.0	9.0 to 10.0	10.0 to 11.0	11.0 to 12.0	12.0 to 13.0
Phosphorus	0.3 max.	0.3 max.	0.3 max.	*	*	*	*	*	*	*
Lead	0.02 max.*	0.02 max.*	0.02 max.*	0.02*	0.02 max.*	0.02 max.*	0.02 max.*	0.02 max.*	0.02 max.*	0.02 max.*
Copper	99.0 min.[b]	remainder	remainder	67.0 min.	94.0 min.	remainder	remainder	remainder	remainder	remainder
Total impurities[a]	0.2 max.	0.5 max.	0.5 max.	4.0 max.	0.5 max.	0.10 max.	0.10 max.	0.10 max.	0.10 max.	0.10 max.

[a] Total impurities, including the elements marked with an asterisk (*), shall not exceed the value specified.
[b] Including silver.

TABLE II.—SUMMARY OF TEST REQUIREMENTS.

Electrode Classification	Chemical Analysis	Hardness Test	All Weld-Metal Tension Test	Guided-Bend Test
E Cu (copper)	all sizes	not required	$\frac{1}{8}$-in. diameter and larger	$\frac{1}{8}$-in. diameter and larger
E CuSn (phosphor bronze)	all sizes	$\frac{1}{8}$-in. diameter and larger	$\frac{1}{8}$-in. diameter and larger	$\frac{1}{8}$-in. diameter and larger
E CuNi (copper-nickel)	all sizes	not required	$\frac{1}{8}$-in. diameter and larger	$\frac{1}{8}$-in. diameter and larger
E CuSi (copper-silicon)	all sizes	$\frac{1}{8}$-in. diameter and larger	$\frac{1}{8}$-in. diameter and larger	$\frac{1}{8}$-in. diameter and larger
E CuAl (aluminum bronze)	all sizes	$\frac{1}{8}$-in. diameter and larger	$\frac{1}{8}$-in. diameter and larger	$\frac{1}{8}$-in. diameter and larger for E CuAl A and E CuAl B. Not required for other classifications.

corners of a specimen during testing shall not be considered.

Retests

8. Retests may be made in accordance with the following:

(*1*) If the all-weld-metal tension test specimen fails, two additional test assemblies shall be prepared and both specimens shall conform to the requirements as to tensile properties prescribed in Table III.

(*2*) If the average hardness does not fall within the range specified in Table III, another pad shall be prepared and tested in accordance with the prescribed requirements.

TABLE III.—MECHANICAL REQUIREMENTS OF ALL-WELD-METAL SPECIMENS.

Electrode Classification	Tensile Strength, min., psi.	Yield Strength (0 5 per cent Extension Under Load), min., psi.	Elongation in 2 in., min., per cent	Brinell Hardness Number
E Cu (copper)	25 000	not specified	20	not specified
E CuSn (phosphor bronze):				
A	40 000	20 000	15	70 to 85 (500-kg. load)
C	45 000	25 000	12	85 to 100 (500-kg. load)
E CuNi (copper-nickel)	45 000	25 000	25	not specified
E CuSi (copper-silicon)	40 000	20 000	20	80 to 100 (500-kg. load)
E CuAl (aluminum bronze):				
A	65 000	30 000	15	130 to 160 (3000-kg. load)
B	70 000	35 000	10	160 to 210 (3000-kg. load)
C	75 000	40 000	4	210 to 260 (3000-kg. load)
D	65 000	45 000	not specified	260 to 310 (3000-kg. load)
E	70 000	50 000	not specified	310 to 365 (3000-kg. load)

(*3*) If either guided-bend test specimen fails, one additional test assembly shall be welded and both specimens removed from this assembly shall meet the prescribed requirements.

Core Wire and Covering

9. (*a*) The diameter of the core wire shall not vary more than plus or minus 0.005 in. from the standard size specified. The length shall not vary more than plus or minus $\frac{1}{4}$ in. from that specified.

(*b*) The covering of all sizes of electrodes shall be concentric to the extent that the maximum core-plus-one-covering dimension shall not exceed the minimum core-plus-one covering dimension by more than 5 per cent. The concentricity shall be measured by any suitable means.

(*c*) The coverings on electrodes shall be such that they are not readily damaged by ordinary handling.

(*d*) Core wire and coverings shall be free of defects which would interfere with uniform performance of the electrodes.

(*e*) The slag produced shall be readily removable.

Exposed Core

10. (*a*) Covered electrodes shall be bare or free from covering for a distance of about $\frac{3}{4}$ in. but not more than $1\frac{1}{4}$ in., for making contact with the holder.

(*b*) The arc end of each electrode shall be sufficiently bare to permit easy striking of the arc. The distance from the arc end to the first point where the full cross-section of the covering prevails shall not exceed the diameter of the core wire. However, for electrodes larger than $\frac{1}{8}$ in., the core wire shall not be exposed around more than one-half the circumference at a distance of $\frac{1}{8}$ in. or more from the arc end.

Standard Sizes and Lengths

11. Standard sizes and lengths of electrodes shall be as shown in the follow-

ing table. In all cases, standard size refers to the diameter of the core wire.

Diameter of Core Wire, in.	Standard Lengths, in.
3/32	9 or 12
1/8, 5/32 and 3/16	14
1/4 and 5/16	18

Note.—End-grip electrodes are standard for all sizes; 18-in. center-grip electrodes may also be used for all sizes.

Packaging for Domestic Use

12. Electrodes shall be suitably packed to insure against injury during shipment or storage in a weather-tight warehouse on dry floors or platforms. Standard packages shall be of 25 and 50 lb. net weight.

Marking

13. All packages shall be legibly marked with the following information:

(*a*) Classification,

(*b*) Manufacturer's name and trade designation,

(*c*) Size, length and net weight, and

(*d*) Guarantee.

Color Markings for Electrode Identification

14. All electrodes shall be color marked in accordance with the current "Standard for Color Markings for Electrode Identification" of the National Electrical Manufacturers Association.

Guarantee

15. The manufacturer shall guarantee that the electrodes in all sizes and classifications conform to these specifications and each container shall be so marked. The manufacturer's responsibility shall be limited to replacement of any electrodes which do not conform to the requirements of these specifications.

Part II.—Details of Tests

Required Tests

16. (*a*) The tests specified in Sections 5, 6 and 7 shall be conducted in accordance with the requirements of Table II and all of the details of testing shall conform to the requirements of this Part II.

(*b*) All welding shall be done in the flat position following the recommendations of the manufacturer as to current, voltage and other factors not specified herein.

(*c*) Mechanical tests shall be made on all sizes of electrodes 1/8 in. and larger. Chemical analyses shall be made on all sizes of electrodes.

Material for Test Plates

17. The base metal to be used for test plates shall conform to the specifications of the American Society for Testing Materials as prescribed in Table IV for the classification under which the electrode is being tested.

TABLE IV.—BASE METAL FOR TEST PLATES.

Classification	Specifications[a] for Base Metal for Test Plates
E Cu (copper)	B 152, type B, annealed; or B 11, grade 2, annealed
E CuSn (phosphor bronze)	B 103, grade A or C, annealed
E CuNi (copper-nickel)	B 122, alloy Nos. 5 or 6, annealed; or B 171 copper-nickel alloy
E CuSi (copper-silicon)	B 96, type A, annealed
E CuAl (aluminum bronze)	B 169, alloy A or C, annealed

[a] These designations refer to the following specifications of the American Society for Testing Materials:
Tentative Specifications for Copper Sheet, Strip and Plate (A.S.T.M. Designation: B 152),[3]
Standard Specifications for Copper Plates for Locomotive Fireboxes (A.S.T.M. Designation: B 11),[4]
Standard Specifications for Phosphor Bronze Plate, Sheet and Strip (A.S.T.M. Designation: B 103),[4]
Tentative Specifications for Copper-Nickel Zinc and Copper-Nickel Alloy Plate, Sheet and Strip (A.S.T.M. Designation: B 122),[3]
Standard Specifications for Copper-Alloy Condenser Tube Plates (A.S.T.M. Designation: B 171),[3]
Standard Specifications for Copper-Silicon Alloy Plate and Sheet for Pressure Vessels (A.S.T.M. Designation: B 96),[4] and
Tentative Specifications for Aluminum Bronze Plate, Sheet and Strip (A.S.T.M. Designation: B 169).[4]

Chemical Analysis and Hardness Test

18. (*a*) To determine the chemical composition of the weld metal and the soundness and Brinell hardness of welded

[3] 1948 Supplement to Book of A.S.T.M Standards, Part I-B.
[4] 1947 Supplement to Book of A.S.T.M Standards, Part I-B.

overlays, pads shall be deposited as prescribed in Paragraphs (*b*) to (*d*), inclusive.

(*b*) Base plates shall be approximately 3 by 5 by $\frac{3}{4}$ in. Weld pads shall be built up in layers to not less than $1\frac{1}{2}$ by 4 by $\frac{1}{2}$ in. in height but shall be not less than six layers. (Pads of $1\frac{1}{2}$ by $2\frac{1}{2}$ by $\frac{1}{2}$ in. in minimum height may be used for those electrode sizes requiring chemical analysis only.) Each layer shall be made up of a series of overlapping lengthwise passes. After completion of each layer, the pad shall be cleaned of any slag and allowed to cool in still air at room temperature (60 F., min.) for about 1 min., and shall then be immersed in boiling water for about 1 min. After removal from the boiling water, the pad shall be allowed to dry thoroughly. Welding shall then be resumed as soon as practicable. The weld metal shall be deposited using the arc amperages and voltages recommended by the manufacturer for production welding under comparable conditions, except that the first three layers of each pad shall be deposited using the minimum applicable current values.

(*c*) The top surface of the pad shall be machined smooth and clean, discarding the metal removed, after which the surface shall be visually examined and shall be free from injurious defects. The Brinell hardness of the weld metal, when required, shall be measured by making nine readings on the surface of the pad, three on the center line parallel to the short dimension of the pad, and three on each end on lines parallel to the center line and approximately $\frac{1}{2}$ in. from each end.

(*d*) For the chemical analysis 2-oz. samples of chips shall then be machined from the pad in such manner that no metal is removed within $\frac{1}{4}$ in. of the base plate or from the first three layers.

All-Weld-Metal Tension Test

19. (*a*) Tension tests shall be made as prescribed in Paragraphs (*b*) to (*d*), using the types of current (and polarity, if d.c.) specified by the manufacturer for each electrode.

(b) Plates shall be restrained during welding sufficiently to prevent warping in excess of 5 deg. A test plate which has warped more than 5 deg. shall be discarded. (Test plates may not be straightened.)

(*c*) Each test assembly shall be within the following temperature ranges before starting to weld each pass. If after any pass the maximum temperature specified below is exceeded, plates shall be allowed to cool in air to within these temperature ranges. (Do not cool in water.)

Classification	Preheat and Interpass Temperature, deg. Fahr.	
	Minimum	Maximum
E Cu	800	1000
E CuSn	350	550
E CuNi	60	212
E CuSi	60	212
E CuAl-A, B and C	250	450
E CuAl-D and E	900	1200

(*d*) One all-weld-metal tension test specimen shall be machined from each finished test assembly as shown in Fig. 1, and shall conform to the requirements as to tensile properties prescribed in Table III.

Guided-Bend Test

20. (*a*) Electrodes in all classifications, $\frac{5}{32}$, $\frac{3}{16}$ and $\frac{1}{4}$ in. in diameter, shall be required to successfully meet the requirements of the guided-bend test as prescribed in Paragraphs (*b*) to (*e*) and Fig. 2.

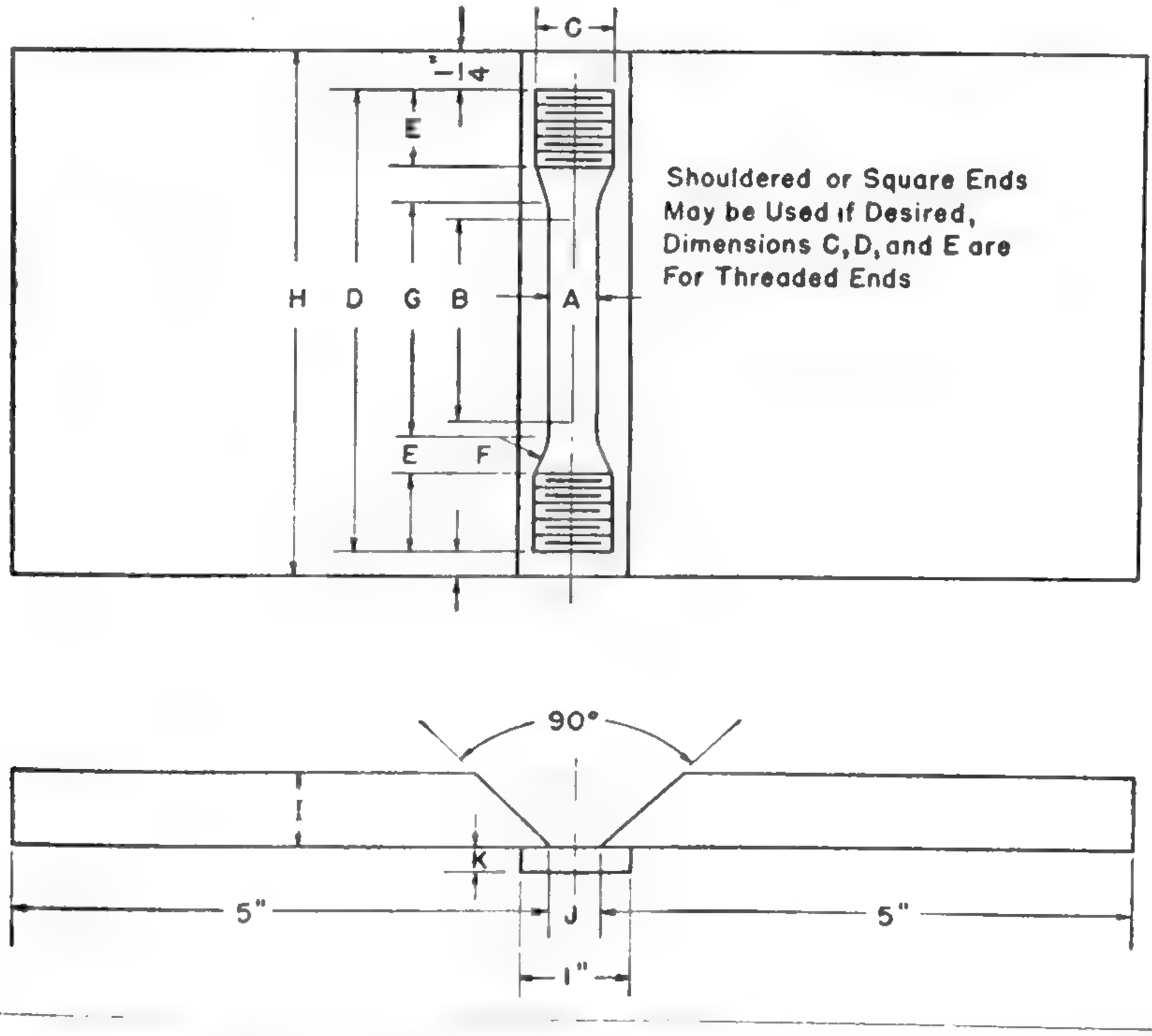
(*b*) Each test assembly shall be within the following temperature ranges before starting to weld each pass. If after any pass the maximum temperature specified below is exceeded, plates shall be allowed

to cool in air to within these temperature ranges. (Do not cool in water.)

Classification	Preheat and Interpass Temperatures, deg Fahr.	
	Minimum	Maximum
E Cu	800	1000
E CuSn	350	550
E CuNi	60	212
E CuSi	60	212
E CuAl-A, B and C	250	450
E CuAl-D and E	900	1200

heated to a temperature of 800 to 850 F. and maintained at that temperature for ½ hr. and then cooled in still air to room temperature (60 F.). Test assemblies for all other classifications shall not be given any postheat treatment.

(d) One face-bend and one root-bend specimen shall be machined from the test assembly as shown in Fig. 3. These specimens conform to Specimens E-1 and F-1 of the American Welding Society's



Electrode Size, in.	Test Plate Thickness, in.	Diameter of Tension Test Specimen, in.	Dimensions of Test Plate and Tension Test Specimen, in.								
	I	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*J*	*K*
⅛ to 5/16, incl.	½	0.252 ± 0.005	1	⅜	2½	½	⅜	1¼	3	½	⅜
3/8 to 5/8, incl.	¾	0.500 ± 0.010	1	¾	4½	¾	⅜	2¼	5	¼	¼

FIG. 1.—Requirements for Preparation of All-Weld-Metal Tension Test Specimens.

(c) After completion of the welding, test assemblies made with electrodes of the E CuSn classifications shall be

Standard Methods for Mechanical Testing of Welds.

(e) Each specimen shall be bent in a

jig having the working contour shown in Fig. 4 and otherwise substantially in accordance with Fig. 4. Any convenient means may be used for moving the plunger member with relation to the die member. The specimen shall be placed on the die member of the jig with the weld at mid-span. Face-bend specimens shall be placed with the face of the weld directed toward the gap; root-bend specimens shall be placed with the root of the weld directed toward the gap. The two members of the jig shall be forced together until the specimen conforms to a U-shape, and until a wire $\frac{1}{32}$ in. in diameter cannot be placed between the specimen and any point on the curvature of the plunger member of the jig. The specimen shall then be removed from the jig, and the convex surface examined.

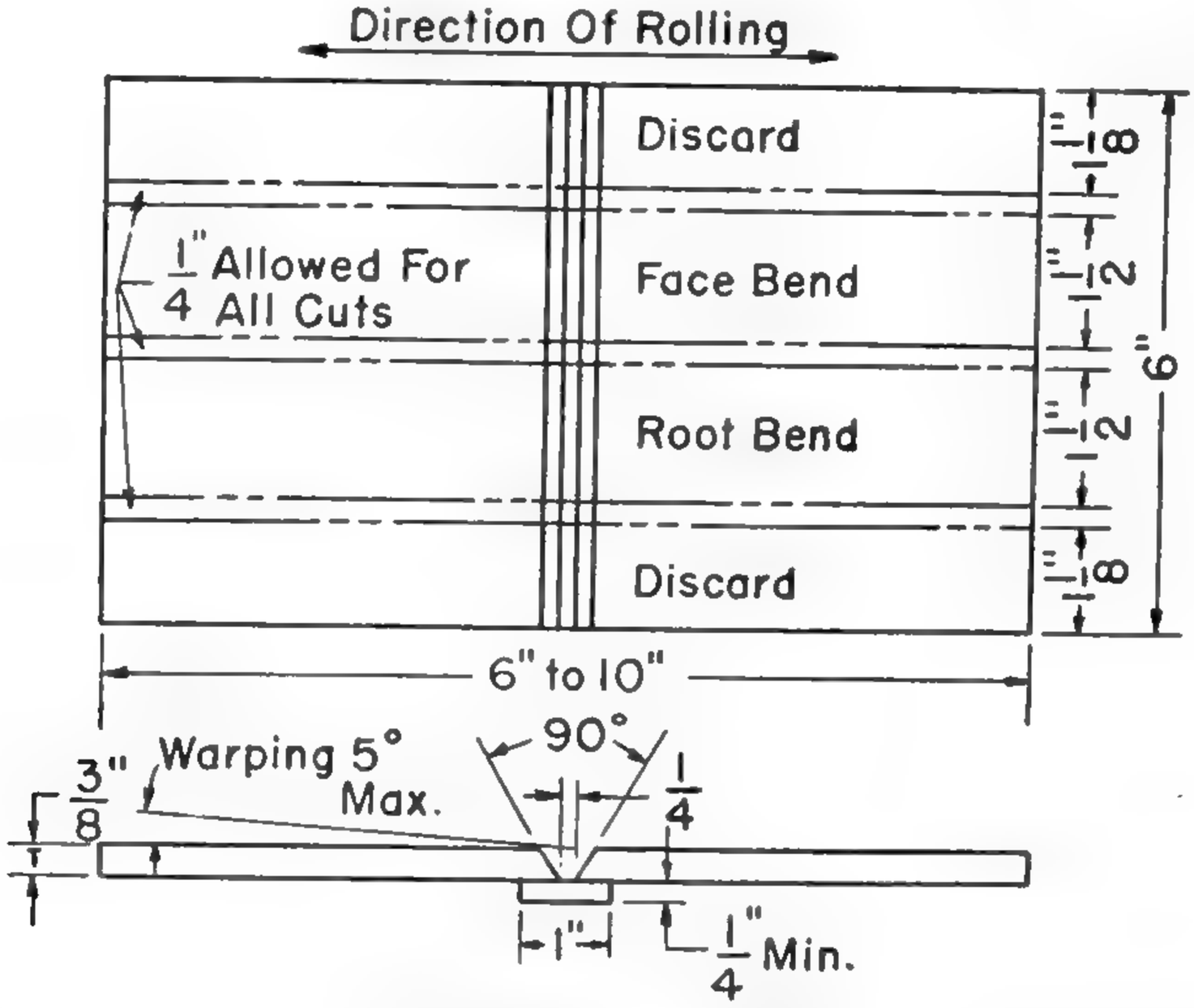
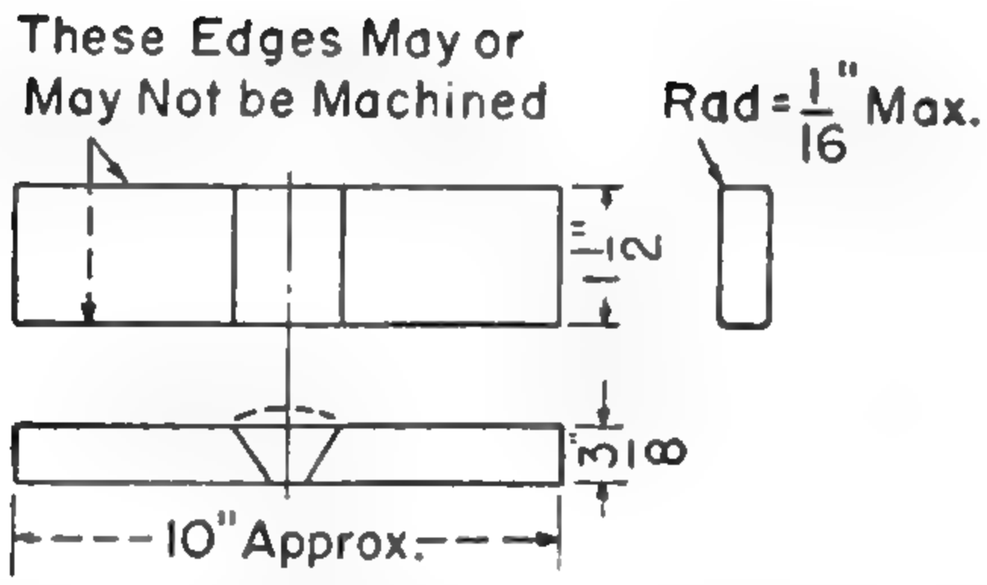


FIG. 2.—Test Joint for Guided-Bend Test.



NOTE.—Weld reinforcement shall be removed flush with the base metal; undercut shall not be removed. All machining shall be done transverse to the weld.

Tension corners of bend specimens shall be broken slightly with a file.

All specimens shall be plainly marked on both ends.

FIG. 3.—Face- and Root-Bend Test Specimens.

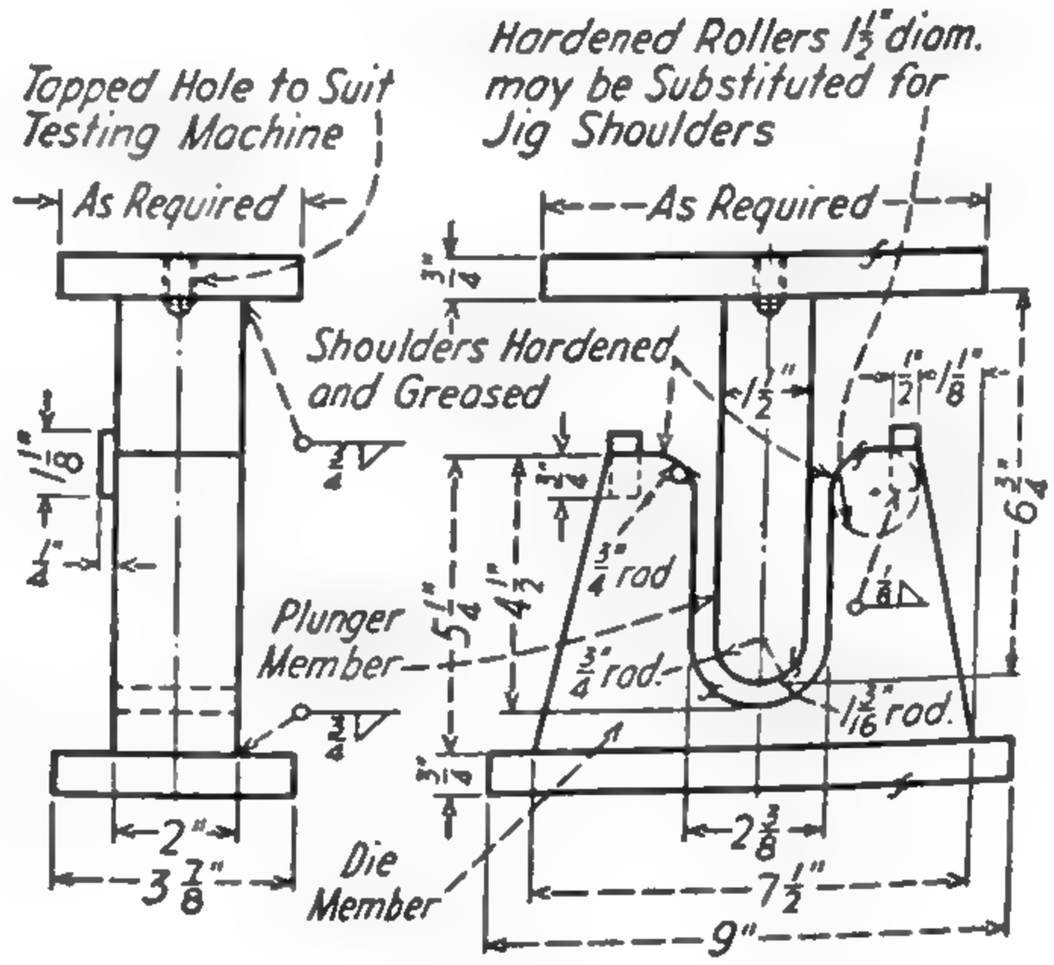


FIG. 4.—Guided-Bend Test Jig.

CHAPTER 62

GENERAL ENGINEERING TABLES*

INTRODUCTION

A HANDBOOK CAN never have too many tables. In preparing the Third Edition of the WELDING HANDBOOK every effort has been made to provide tabular information in the respective chapters on the welding processes and their use for different metals and in different applications.

In this chapter there has been included a compilation of tables of a more general engineering nature, intended to provide the need for related data, such as temperature conversion, material thicknesses, hardness, etc., in the welding shop and office. The tables have been selected to be most useful and to help in providing data most needed. Information not provided will be found in basic engineering handbooks. While there is no general sequence for the tables in this chapter, it will be found that related subjects have been grouped together.

NOTES

Table 1

The chart shown as Table 1 not only lists the melting points of various alloys and metals but also serves as a convenient means for conversion between Centigrade and Fahrenheit temperature scales. In addition, at the far right of the scale are shown the color designations that are commonly used in judging the temperatures of hot metal by color.

Melting Points.—This chart should prove useful to all welding personnel for it contains basic information on working with metals at elevated temperatures. Reference to the chart, for instance, shows why aluminum and aluminum alloys, because of their low melting points, give little or no indication by change in color when they approach welding heat. On the other hand, the high melting point of wrought iron explains why considerably more heat is required to weld this metal than is required for cast iron, for instance.

Temperature Color Scale.—Another use for the chart is in estimating the temperature by color. For instance, instructions may require that the part be preheated to 1100°F. before welding. If you are without a thermocouple or other means for accurately measuring high temperatures, reference to the chart shows that the part, at 1100°F., would have a blood-red color. With a little experience, you can estimate this fairly closely by eye. In this connection, it should be mentioned that the color scale is for observations made in a fairly dark place and without welding goggles. As the light increases, the color groups on the scale will apply to higher temperatures.

Conversion Data.—Finally, the chart is a ready means for converting Fahrenheit to Centigrade, and vice versa. Suppose you are familiar with the Fahrenheit scale, yet instructions call for the quenching of a welded part from 900°C. Reference to the chart shows this to be approximately 1650°F. (see also Table 2).

Table 2

In using Table 2 for temperature conversion it is well to bear in mind two formulas which will come in handy if the accompanying tables are not at hand. To convert Fahrenheit to Centrigrade the formula is

$$C.^\circ = {}^5/_9\ (F.^\circ - 32)$$
$$= {}^5/_9\ (F.^\circ + 40)\ -40$$

To convert Centrigrade temperature to Fahrenheit the formula is

$$F.^\circ = {}^9/_5\ C.^\circ + 32 = {}^9/_5\ (C.^\circ + 40)\ -40$$

---

* Prepared by T. B. Jefferson, Editor, *The Welding Engineer.*

Table 4

While the hardness conversion table (Table 4) is self-explanatory it might be well to recall a few of the basic facts connected with the determination of the hardness of a material. It is extremely important that conversions from Brinell to Rockwell or Vickers be limited to materials that are of uniform hardness to a depth of at least ten times the depth of the indentation. It should also be remembered that in the Brinell test the steel balls tend to flatten slightly more than carbide balls, resulting in larger indentation and lower Brinell number than shown by carbide balls. When taking hardness by means of a Shore Scleroscope, it should be remembered that readings are affected by variation in mass, form, surface composition and physical condition of the different specimens under test.

Table 6

The unit of length of the metric system is the meter. The meter is 39.370147 in. in length. The meter is divided into centimeters (0.01 meter) or millimeters (0.001 meter). When the occasion arises millimeters may be converted into fractions of an inch or inches and fractions into millimeters by use of the accompanying Table 6.

Table 7

When determining the thickness or diameter of material given by gage number (Table 7), it should be remembered that U.S. Standard gage is used for iron and steel sheets. This gage, which was established by an act of Congress in 1893, has a gage number which is determined by the weight per square foot rather than the thickness of the material. Birmingham or Stubs gage is used to determine the thickness of hot- and cold-rolled strips, round edge flat wire, spring steel, brass, copper, stainless steel, steel tubing and boiler tubes. Brown and Sharpe or American gage is used with copper, brass and phosphor bronze stock in sheets, bars and wire. U.S. Standard gage applies to round steel wire in black annealed, bright basic, galvanized, tinned and copper coated finishes.

Several reference formulas are handy for determining the weight of steel stock. Based on a weight of 489.54 lb. per cu. ft. for steel it will be found that the weight in pounds per foot of any size round bar is $2.67d^2$; any size octagonal bar, $2.82d^2$; any size hexagonal bar, $2.94d^2$; any size flat or square bar, $3.40\ wt$, where d is the diameter or distance between opposite faces, w is the width and t is the thickness; in all cases the dimensions are in inches.

Table 12

All matter is composed of one or a combination of two or more of the 96 elements which make up the periodic table. About 20 of these 96 elements are used in the manufacture of carbon and alloy steels. Some are used because of the specific properties they impart to steel when alloyed with it, others to rid the steel of impurities or to render impurities harmless.

Copper is particularly friendly to the other elements; it alloys with at least thirty of them. Seventeen elements are used in making commercial copper alloys. The 96 elements of the periodic table together with their chemical symbols are listed in Table 12.

TABLE 1

TEMPERATURE DATA FOR METALS AND ALLOYS

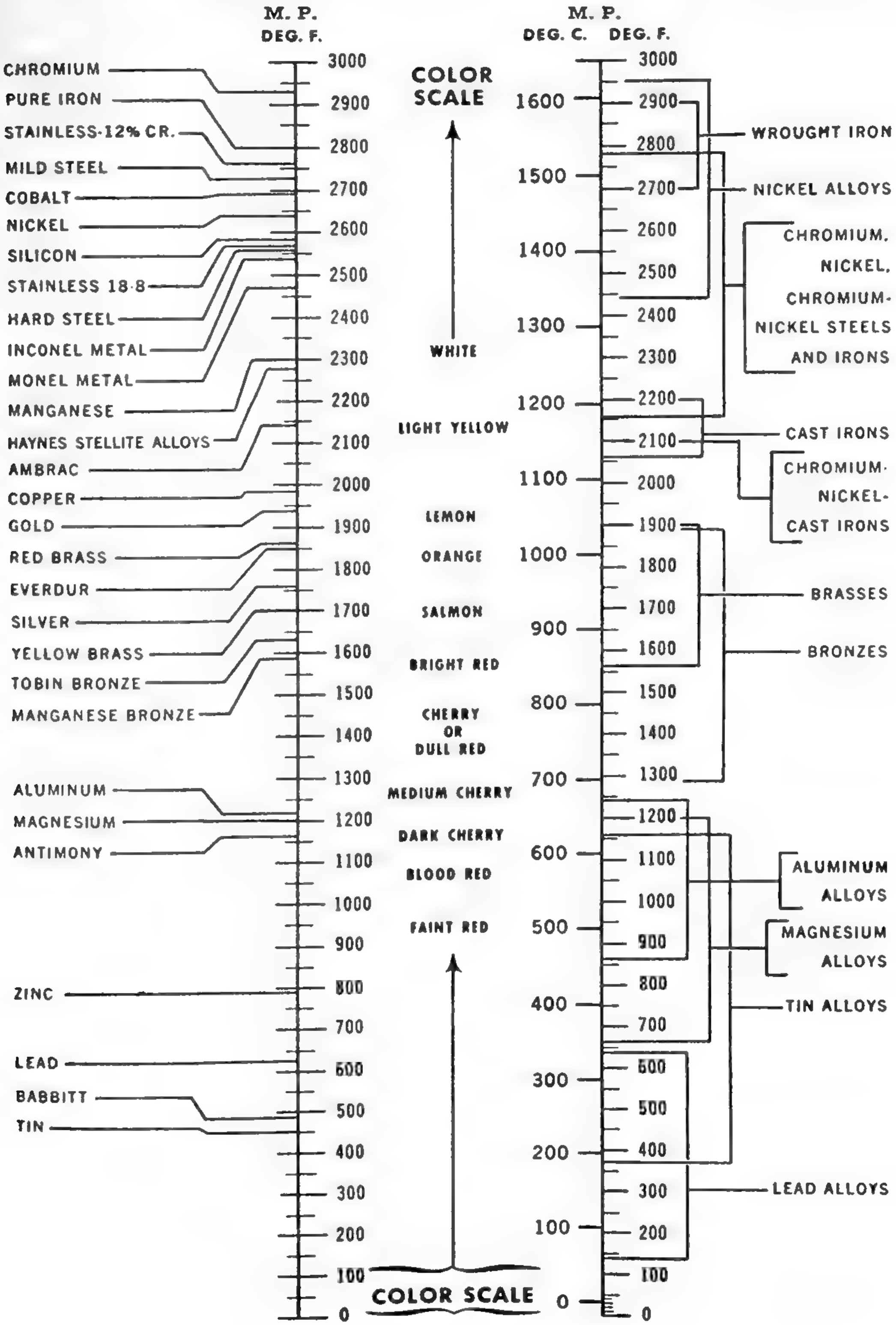


TABLE 2

−459.4 to 0			0 to 100						100 to 1000					
C		F	C		F	C		F	C		F	C		F
−273	*−459.4*		−17.8	*0*	32	10.0	*50*	122.0	38	*100*	212	260	*500*	932
−268	*−450*		−17.2	*1*	33.8	10.6	*51*	123.8	43	*110*	230	266	*510*	950
−262	*−440*		−16.7	*2*	35.6	11.1	*52*	125.6	49	*120*	248	271	*520*	968
−257	*−430*		−16.1	*3*	37.4	11.7	*53*	127.4	54	*130*	266	277	*530*	986
−251	*−420*		−15.6	*4*	39.2	12.2	*54*	129.2	60	*140*	284	282	*540*	1004
−246	*−410*		−15.0	*5*	41.0	12.8	*55*	131.0	66	*150*	302	288	*550*	1022
−240	*−400*		−14.4	*6*	42.8	13.3	*56*	132.8	71	*160*	320	293	*560*	1040
−234	*−390*		−13.9	*7*	44.6	13.9	*57*	134.6	77	*170*	338	299	*570*	1058
−229	*−380*		−13.3	*8*	46.4	14.4	*58*	136.4	82	*180*	356	304	*580*	1076
−223	*−370*		−12.8	*9*	48.2	15.0	*59*	138.2	88	*190*	374	310	*590*	1094
−218	*−360*		−12.2	*10*	50.0	15.6	*60*	140.0	93	*200*	392	316	*600*	1112
−212	*−350*		−11.7	*11*	51.8	16.1	*61*	141.8	99	*210*	410	321	*610*	1130
−207	*−340*		−11.1	*12*	53.6	16.7	*62*	143.6	100	*212*	413.6	327	*620*	1148
−201	*−330*		−10.6	*13*	55.4	17.2	*63*	145.4	104	*220*	428	332	*630*	1166
−196	*−320*		−10.0	*14*	57.2	17.8	*64*	147.2	110	*230*	446	338	*640*	1184
−190	*−310*		− 9.4	*15*	59.0	18.3	*65*	149.0	116	*240*	464	343	*650*	1202
−184	*−300*		− 8.9	*16*	60.8	18.9	*66*	150.8	121	*250*	482	349	*660*	1220
−179	*−290*		− 8.3	*17*	62.6	19.4	*67*	152.6	127	*260*	500	354	*670*	1238
−173	*−280*		− 7.8	*18*	64.4	20.0	*68*	154.4	132	*270*	518	360	*680*	1256
−169	*−273*	−459.4	− 7.2	*19*	66.2	20.6	*69*	156.2	138	*280*	536	366	*690*	1274
−168	*−270*	−454	− 6.7	*20*	68.0	21.1	*70*	158.0	143	*290*	554	371	*700*	1292
−162	*−260*	−436	− 6.1	*21*	69.8	21.7	*71*	159.8	149	*300*	572	377	*710*	1310
−157	*−250*	−418	− 5.6	*22*	71.6	22.2	*72*	161.6	154	*310*	590	382	*720*	1328
−151	*−240*	−400	− 5.0	*23*	73.4	22.8	*73*	163.4	160	*320*	608	388	*730*	1346
−146	*−230*	−382	− 4.4	*24*	75.2	23.3	*74*	165.2	166	*330*	626	393	*740*	1364
−140	*−220*	−364	− 3.9	*25*	77.0	23.9	*75*	167.0	171	*340*	644	399	*750*	1382
−134	*−210*	−346	− 3.3	*26*	78.8	24.4	*76*	168.8	177	*350*	662	404	*760*	1400
−129	*−200*	−328	− 2.8	*27*	80.6	25.0	*77*	170.6	182	*360*	680	410	*770*	1418
−123	*−190*	−310	− 2.2	*28*	82.4	25.6	*78*	172.4	188	*370*	698	416	*780*	1436
−118	*−180*	−292	− 1.7	*29*	84.2	26.1	*79*	174.2	193	*380*	716	421	*790*	1454
−112	*−170*	−274	− 1.1	*30*	86.0	26.7	*80*	176.0	199	*390*	734	427	*800*	1472
−107	*−160*	−256	− 0.6	*31*	87.8	27.2	*81*	177.8	204	*400*	752	432	*810*	1490
−101	*−150*	−238	0.0	*32*	89.6	27.8	*82*	179.6	210	*410*	770	438	*820*	1508
− 96	*−140*	−220	0.6	*33*	91.4	28.3	*83*	181.4	216	*420*	788	443	*830*	1526
− 90	*−130*	−202	1.1	*34*	93.2	28.9	*84*	183.2	221	*430*	806	449	*840*	1544
− 84	*−120*	−184	1.7	*35*	95.0	29.4	*85*	185.0	227	*440*	824	454	*850*	1562
− 79	*−110*	−166	2.2	*36*	96.8	30.0	*86*	186.8	232	*450*	842	460	*860*	1580
− 73	*−100*	−148	2.8	*37*	98.6	30.6	*87*	188.6	238	*460*	860	466	*870*	1598
− 68	*− 90*	−130	3.3	*38*	100.4	31.1	*88*	190.4	243	*470*	878	471	*880*	1616
− 62	*− 80*	−112	3.9	*39*	102.2	31.7	*89*	192.2	249	*480*	896	477	*890*	1634
− 57	*− 70*	− 94	4.4	*40*	104.0	32.2	*90*	194.0	254	*490*	914	482	*900*	1652
− 51	*− 60*	− 76	5.0	*41*	105.8	32.8	*91*	195.8				488	*910*	1670
− 46	*− 50*	− 58	5.6	*42*	107.6	33.3	*92*	197.6				493	*920*	1688
− 40	*− 40*	− 40	6.1	*43*	109.4	33.9	*93*	199.4				499	*930*	1706
− 34	*− 30*	− 22	6.7	*44*	111.2	34.4	*94*	201.2				504	*940*	1724
− 29	*− 20*	− 4	7.2	*45*	113.0	35.0	*95*	203.0				510	*950*	1742
− 23	*− 10*	14	7.8	*46*	114.8	35.6	*96*	204.8				516	*960*	1760
− 17.8	*0*	32	8.3	*47*	116.6	36.1	*97*	206.6				521	*970*	1778
			8.9	*48*	118.4	36.7	*98*	208.4				527	*980*	1796
			9.4	*49*	120.2	37.2	*99*	210.2				532	*990*	1814
						37.8	*100*	212.0				538	*1000*	1832

[a] Look up reading in middle column. If in degrees Centigrade, read Fahrenheit equivalent in right-hand column; if in Fahrenheit degrees, read Centigrade equivalent in left-hand column.

TEMPERATURE CONVERSION TABLES[a]

1000 to 2000						2000 to 3000					
C		F	C		F	C		F	C		F
538	*1000*	1832	816	*1500*	2732	1093	*2000*	3632	1371	*2500*	4532
543	*1010*	1850	821	*1510*	2750	1099	*2010*	3650	1377	*2510*	4550
549	*1020*	1868	827	*1520*	2768	1104	*2020*	3668	1382	*2520*	4568
554	*1030*	1886	832	*1530*	2786	1110	*2030*	3686	1388	*2530*	4586
560	*1040*	1904	838	*1540*	2804	1116	*2040*	3704	1393	*2540*	4604
566	*1050*	1922	843	*1550*	2822	1121	*2050*	3722	1399	*2550*	4622
571	*1060*	1940	849	*1560*	2840	1127	*2060*	3740	1404	*2560*	4640
577	*1070*	1958	854	*1570*	2858	1132	*2070*	3758	1410	*2570*	4658
582	*1080*	1976	860	*1580*	2876	1138	*2080*	3776	1416	*2580*	4676
588	*1090*	1994	866	*1590*	2894	1143	*2090*	3794	1421	*2590*	4694
593	*1100*	2012	871	*1600*	2912	1149	*2100*	3812	1427	*2600*	4712
599	*1110*	2030	877	*1610*	2930	1154	*2110*	3830	1432	*2610*	4730
604	*1120*	2048	882	*1620*	2948	1160	*2120*	3848	1438	*2620*	4748
610	*1130*	2066	888	*1630*	2966	1166	*2130*	3866	1443	*2630*	4766
616	*1140*	2084	893	*1640*	2984	1171	*2140*	3884	1449	*2640*	4784
621	*1150*	2102	899	*1650*	3002	1177	*2150*	3902	1454	*2650*	4802
627	*1160*	2120	904	*1660*	3020	1182	*2160*	3920	1460	*2660*	4820
632	*1170*	2138	910	*1670*	3038	1188	*2170*	3938	1466	*2670*	4838
638	*1180*	2156	916	*1680*	3056	1193	*2180*	3956	1471	*2680*	4856
643	*1190*	2174	921	*1690*	3074	1199	*2190*	3974	1477	*2690*	4874
649	*1200*	2192	927	*1700*	3092	1204	*2200*	3992	1482	*2700*	4892
654	*1210*	2210	932	*1710*	3110	1210	*2210*	4010	1488	*2710*	4910
660	*1220*	2228	938	*1720*	3128	1216	*2220*	4028	1493	*2720*	4928
666	*1230*	2246	943	*1730*	3146	1221	*2230*	4046	1499	*2730*	4946
671	*1240*	2264	949	*1740*	3164	1227	*2240*	4064	1504	*2740*	4964
677	*1250*	2282	954	*1750*	3182	1232	*2250*	4082	1510	*2750*	4982
682	*1260*	2300	960	*1760*	3200	1238	*2260*	4100	1516	*2760*	5000
688	*1270*	2318	966	*1770*	3218	1243	*2270*	4118	1521	*2770*	5018
693	*1280*	2336	971	*1780*	3236	1249	*2280*	4136	1527	*2780*	5036
699	*1290*	2354	977	*1790*	3254	1254	*2290*	4154	1532	*2790*	5054
704	*1300*	2372	982	*1800*	3272	1260	*2300*	4172	1538	*2800*	5072
710	*1310*	2390	988	*1810*	3290	1266	*2310*	4190	1543	*2810*	5090
716	*1320*	2408	993	*1820*	3308	1271	*2320*	4208	1549	*2820*	5108
721	*1330*	2426	999	*1830*	3326	1277	*2330*	4226	1554	*2830*	5126
727	*1340*	2444	1004	*1840*	3344	1282	*2340*	4244	1560	*2840*	5144
732	*1350*	2462	1010	*1850*	3362	1288	*2350*	4262	1566	*2850*	5162
738	*1360*	2480	1016	*1860*	3380	1293	*2360*	4280	1571	*2860*	5180
743	*1370*	2498	1021	*1870*	3398	1299	*2370*	4298	1577	*2870*	5198
749	*1380*	2516	1027	*1880*	3416	1304	*2380*	4316	1582	*2880*	5216
754	*1390*	2534	1032	*1890*	3434	1310	*2390*	4334	1588	*2890*	5234
760	*1400*	2552	1038	*1900*	3452	1316	*2400*	4352	1593	*2900*	5252
766	*1410*	2570	1043	*1910*	3470	1321	*2410*	4370	1599	*2910*	5270
771	*1420*	2588	1049	*1920*	3488	1327	*2420*	4388	1604	*2920*	5288
777	*1430*	2606	1054	*1930*	3506	1332	*2430*	4406	1610	*2930*	5306
782	*1440*	2624	1060	*1940*	3524	1338	*2440*	4424	1616	*2940*	5324
788	*1450*	2642	1066	*1950*	3542	1343	*2450*	4442	1621	*2950*	5342
793	*1460*	2660	1071	*1960*	3560	1349	*2460*	4460	1627	*2960*	5360
799	*1470*	2678	1077	*1970*	3578	1354	*2470*	4478	1632	*2970*	5378
804	*1480*	2696	1082	*1980*	3596	1360	*2480*	4496	1638	*2980*	5396
810	*1490*	2714	1088	*1990*	3614	1366	*2490*	4514	1643	*2990*	5414
			1093	*2000*	3632				1649	*3000*	5432

C.° = $^5/_9$ (F.° − 32) = $^5/_9$ (F.° + 40) − 40. F.° = $^9/_5$ C.° + 32 = $^9/_5$ (C.° + 40) − 40.

TABLE 3
EXPANSION OF METALS

The accompanying nomograph chart (Table 3) will be found useful for quickly determining the expansion of any ordinary metals—such as mild steel, wrought iron, copper, brass—or any material having an expansion coefficient between the limits 0.000005 and 0.000012 in. per ft. per °F. of temperature change. The chart handles any length from 20 to 10,000 ft.

For example, how much will 850 ft. of wrought iron pipe expand when the Temperature increase is 300°F.? Refering to the chart, the answer is obtained by connecting 300, column *C*, with the coefficient of expansion of wrought iron, column *E*, and locating the intersection with column *D*. Then from the point of intersection, project a line to 850, column *A*, and the expansion is found to be 20 in. in column *B*.

The temperature difference, column *C*, is found by subtracting the minimum from the maximum temperature. Thus a steam pipe at its coldest may be 40°F; at its hottest it may be 740°F. The difference is therefore 740—40 or 700°F.

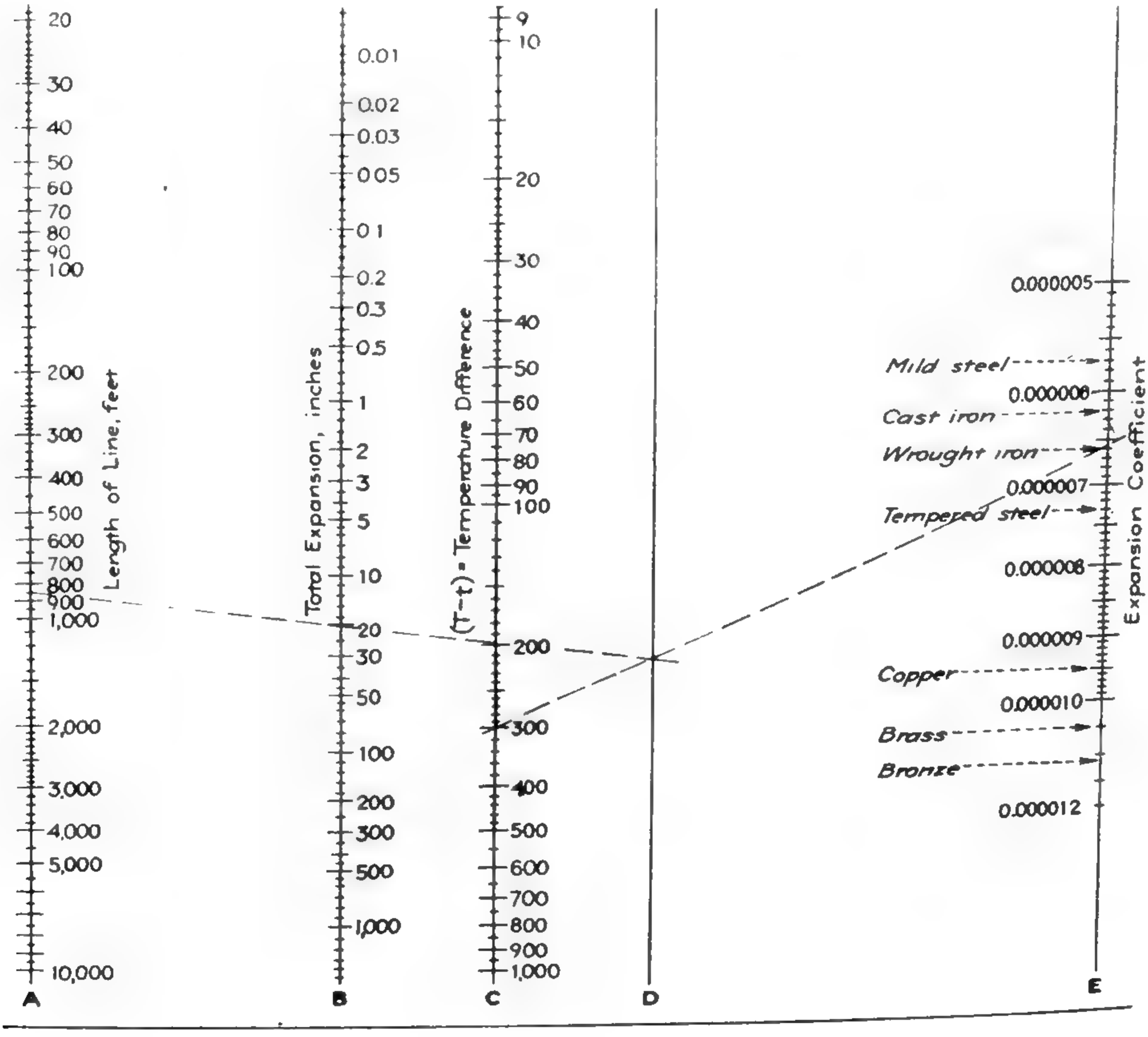


TABLE 4.

HARDNESS CONVERSION FOR STEEL

Brinell Indentation Diameter, mm.	Brinell Hardness Number: 10-mm. Standard Ball, 3000-kg. Load	Brinell Hardness Number: 10-mm. Hultgren Ball, 3000-kg. Load [a]	Brinell Hardness Number: 10-mm. Carbide Ball, 3000-kg. Load	Diamond Pyramid Hardness Number	Rockwell Hardness Number: C Scale, 150-kg. Load, Brale Penetrator	Rockwell Hardness Number: A Scale, 60-kg. Load, Brale Penetrator	Rockwell Hardness Number: D Scale, 100-kg. Load, Brale Penetrator	Rockwell Superficial Hardness Number: 15-N Scale, 15-kg. Load, Superficial Brale Penetrator	Rockwell Superficial Hardness Number: 30-N Scale, 30-kg. Load, Superficial Brale Penetrator	Rockwell Superficial Hardness Number: 45-N Scale, 45-kg. Load Superficial Brale Penetrator	Brinell Indentation Diameter, mm.
2.35	•	..	682	737	61.7	82.2	72.0	91.0	79.0	68.5	2.35
2.40	•	..	653	697	60.0	81.2	70.7	90.2	77.5	66.5	2.40
2.45	•	..	627	667	58.7	80.5	69.7	89.6	76.3	65.1	2.45
2.50	•	..	..	677	59.1	80.7	70.0	89.8	76.8	65.7	2.50
	..	601	601	640	57.3	79.8	68.7	89.0	75.1	63.5	
2.55	•	..	..	640	57.3	79.8	68.7	89.0	75.1	63.5	2.55
	..	578	578	615	56.0	79.1	67.7	88.4	73.9	62.1	
2.60	•	..	..	607	55.6	78.8	67.4	88.1	73.5	61.6	2.60
	..	555	555	591	54.7	78.4	66.7	87.8	72.7	60.6	
2.65	•	..	..	579	54.0	78.0	66.1	87.5	72.0	59.8	2 65
	..	534	534	569	53.5	77.8	65.8	87.2	71.6	59.2	
2.70	•	..	..	553	52.5	77.1	65.0	86.7	70.7	58.0	2.70
	..	514	514	547	52.1	76.9	64.7	86.5	70.3	57.6	
2.75	495	..	..	539	51.6	76.7	64.3	86.3	69.9	56.9	2.75
	..	495	..	530	51.1	76.4	63.9	86.0	69.5	56.2	
	..	..	495	528	51.0	76.3	63.8	85.9	69.4	56.1	
2.80	477	..	..	516	50.3	75.9	63.2	85.6	68.7	55.2	2.80
	..	477	.	508	49.6	75.6	62.7	85.3	68.2	54.5	
	..	..	477	508	49.6	75.6	62.7	85.3	68.2	54.5	
2.85	461	..	..	495	48.8	75.1	61.9	84.9	67.4	53.5	2.85
	..	461	.	491	48.5	74.9	61.7	84.7	67.2	53.2	
	..	..	461	491	48.5	74.9	61.7	84.7	67.2	53.2	
2.90	444	..	.	474	47.2	74.3	61.0	84.1	66.0	51.7	2.90
	..	444	.	472	47.1	74.2	60.8	84.0	65.8	51.5	
	..	..	444	472	47.1	74.2	60.8	84.0	65.8	51.5	
2.95	429	429	429	455	45.7	73.4	59.7	83.4	64.6	49.9	2.95
3.00	415	415	415	440	44.5	72.8	58.8	82.8	63.5	48.4	3.00
3.05	401	401	401	425	43.1	72.0	57.8	82.0	62.3	46.9	3.05
3.10	388	388	388	410	41.8	71.4	56.8	81.4	61.1	45.3	3.10
3.15	375	375	375	396	40.4	70.6	55.7	80.6	59.9	43.6	3.15
3.20	363	363	363	383	39.1	70.0	54.6	80.0	58.7	42.0	3.20
3.25	352	352	352	372	37.9	69.3	53.8	79.3	57.6	40.5	3.25
3.30	341	341	341	360	36.6	68.7	52.8	78.6	56.4	39.1	3.30
3.35	331	331	331	350	35.5	68.1	51.9	78.0	55.4	37.8	3.35
3.40	321	321	321	339	34.3	67.5	51.0	77.3	54.3	36.1	3.40
3.45	311	311	311	328	33.1	66.9	50.0	76.7	53.3	34.4	3.45
3.50	302	302	302	319	32.1	66.3	49.3	76.1	52.2	33.8	3.50
3.55	293	293	293	309	30.9	65.7	48.3	75.5	51.2	32.4	3.55
3.60	285	285	285	301	29.9	65.3	47.6	75.0	50.3	31.2	3.60
3.65	277	277	277	292	28.8	64.6	46.7	74.4	49.3	29.9	3.65
3.70	269	269	269	284	27.6	64.1	45.9	73.7	48.3	28.5	3.70
3.75	262	262	262	276	26.6	63.6	45.0	73.1	47.3	27.3	3.75
3.80	255	255	255	269	25.4	63.0	44.2	72.5	46.2	26.0	3.80
3.85	248	248	248	261	24.2	62.5	43.2	71.7	45.1	24.5	3.85
3.90	241	241	241	253	22.8	61.8	42.0	70.9	43.9	22.8	3.90
3.95	235	235	235	247	21.7	61.4	41.4	70.3	42.9	21.5	3.95
4.00	229	229	229	241	20.5	60.8	40.5	69.7	41.9	20.1	4.00

[a] No Brinell hardness values are given above 500 Brinell hardness number for the 10-mm. standard steel ball in conformance with limitations established by the Standard Method of Test for Brinell Hardness of Metallic Materials (A.S.T.M. Designation: E 10).

[a] Brinell hardness values are given for the Hultgren ball to 601 Brinell hardness; however, flattening of the ball at the higher hardnesses gives lower Brinell hardness values than obtained with the carbide ball. For example, material having a D.P.H. value of 667 has a carbide ball Brinell hardness of 627, while material having a D.P.H. value of 677 has a Hultgren ball Brinell hardness of only 601.

TABLE 5

FOOT DECIMAL EQUIVALENTS FOR INCHES AND FRACTIONS OF AN INCH

1/2's	1/4's	1/8's	1/16's	1/32's	1/64's	0″	1″	2″	3″	4″	5″	6″	7″	8″	9″	10″	11″
					0	.0000	.0833	.1667	.2500	.3333	.4167	.5000	.5833	.6667	.7500	.8333	.9167
					1	.0013	.0846	.1680	.2513	.3346	.4180	.5013	.5846	.6680	.7513	.8346	.9180
				1	2	.0026	.0859	.1693	.2526	.3359	.4193	.5026	.5859	.6693	.7526	.8359	.9193
					3	.0039	.0872	.1706	.2539	.3372	.4206	.5039	.5872	6706	.7539	.8372	.9206
			1	2	4	.0052	.0885	.1719	.2552	.3385	.4219	.5052	.5885	.6719	.7552	.8385	.9219
					5	.0065	.0898	.1732	.2565	.3398	.4232	.5065	.5898	.6732	.7565	.8398	.9232
				3	6	.0078	.0911	.1745	.2578	.3411	.4245	.5078	.5911	.6745	.7578	.8411	.9245
					7	.0091	.0924	.1758	.2591	.3424	.4258	.5091	.5924	.6758	.7591	.8424	.9258
		1	2	4	8	.0104	.0938	.1771	.2604	.3438	.4271	.5104	.5938	.6771	.7604	.8438	.9271
					9	.0117	.0951	.1784	.2617	.3451	.4284	.5117	.5951	.6784	.7617	.8451	.9284
				5		.0130	.0964	.1797	.2630	.3464	.4297	.5130	.5964	.6797	.7630	.8464	.9297
					11	.0143	.0977	.1810	.2643	.3477	.4310	.5143	.5977	.6810	.7643	.8477	.9310
			3	6		.0156	.0990	.1823	.2656	.3490	.4323	.5156	.5990	.6823	.7656	.8490	.9323
					13	.0169	.1003	.1836	.2669	.3503	.4336	.5169	.6003	.6836	.7669	.8503	.9336
				7		.0182	1016	.1849	.2682	.3516	.4349	.5182	.6016	.6849	.7682	.8516	.9349
					15	.0195	1029	.1862	.2695	.3529	.4362	.5195	.6029	.6862	.7695	.8529	.9362
	1	2	4	8		.0208	.1042	.1875	.2708	.3542	.4375	.5208	.6042	.6875	.7708	.8542	.9375
					17	.0221	.1055	.1888	.2721	.3555	.4388	.5221	.6055	.6888	.7721	.8555	.9388
				9		.0234	.1068	.1901	.2734	.3568	.4401	.5234	.6068	.6901	.7734	.8568	.9401
					19	.0247	.1081	.1914	.2747	.3581	.4414	.5247	.6081	.6914	.7747	.8581	.9414
			5	10		.0260	.1094	.1927	.2760	.3594	.4427	.5260	.6094	.6927	.7760	.8594	.9427
					21	.0273	.1107	.1940	.2773	.3607	.4440	.5273	.6107	.6940	.7773	.8607	.9440
				11		.0286	.1120	.1953	.2786	.3620	.4453	.5286	.6120	.6953	.7786	.8620	.9453
					23	.0299	.1133	.1966	.2799	.3633	.4466	.5299	.6133	.6966	.7799	.8633	.9466
		3	6	12		.0313	.1146	.1979	.2813	.3646	.4479	.5313	.6146	.6979	.7813	.8646	.9479
					25	.0326	.1159	.1992	.2826	.3659	.4492	.5326	.6159	.6992	.7826	.8659	.9492
				13		.0339	.1172	.2005	.2839	.3672	.4505	.5339	.6172	.7005	.7839	.8672	.9505
					27	.0352	.1185	.2018	.2852	.3685	.4518	.5352	.6185	.7018	.7852	.8685	.9518
			7	14		.0365	.1198	.2031	.2865	.3698	.4531	.5365	.6198	.7031	.7865	.8698	.9531

1/2's	1/4's	1/8's	1/16's	1/32's	1/64's	0"	1"	2"	3"	4"	5"	6"	7"	8"	9"	10"	11"
					29	.0378	.1211	.2044	.2878	.3711	.4544	.5378	.6211	.7044	.7878	.8711	.9544
				15		.0391	.1224	.2057	.2891	.3724	.4557	.5391	.6224	.7057	.7891	.8724	.9557
					31	.0404	.1237	.2070	.2904	.3737	.4570	.5404	.6237	.7070	.7904	.8737	.9570
1	2	4	8	16		.0417	.1250	.2083	.2917	.3750	.4583	.5417	.6250	.7083	.7917	.8750	.9583
					33	.0430	.1263	.2096	.2930	.3763	.4596	.5430	.6263	.7096	.7930	.8763	.9596
				17		.0443	.1276	.2109	.2943	.3776	.4609	.5443	.6276	.7109	.7943	.8776	.9609
					35	.0456	.1289	.2122	.2956	.3789	.4622	.5456	.6289	.7122	.7956	.8789	.9622
			9	18		.0469	.1302	.2135	.2969	.3802	.4635	.5469	.6302	.7135	.7969	.8802	.9635
					37	.0482	.1315	.2148	.2982	.3815	.4648	.5482	.6315	.7148	.7982	.8815	.9648
				19		.0495	.1328	.2161	.2995	.3828	.4661	.5495	.6328	.7161	.7995	.8828	.9661
					39	.0508	.1341	.2174	.3008	.3841	.4674	.5508	.6341	.7174	.8008	.8841	.9674
		5	10	20		.0521	.1354	.2188	.3021	.3854	.4688	.5521	.6354	.7188	.8021	.8854	.9688
					41	.0534	.1367	.2201	.3034	.3867	.4701	.5534	.6367	.7201	.8034	.8867	.9701
				21		.0547	.1380	.2214	.3047	.3880	.4714	.5547	.6380	.7214	.8047	.8880	.9714
					43	.0560	.1393	.2227	.3060	.3893	.4727	.5560	.6393	.7227	.8060	.8893	.9727
			11	22		.0573	1406	.2240	.3073	.3906	.4740	.5573	.6406	.7240	.8073	.8906	.9740
					45	.0586	.1419	.2253	.3086	.3919	.4753	.5586	.6419	.7253	.8086	.8919	.9753
				23		.0599	.1432	.2266	.3099	.3932	.4766	.5599	.6432	.7266	.8099	.8932	.9766
					47	.0612	.1445	.2279	.3112	.3945	.4779	.5612	.6445	.7279	.8112	.8945	.9779
	3	6	12	24		.0625	.1458	.2292	.3125	.3958	.4792	.5625	.6458	.7292	.8125	.8958	.9792
					49	.0638	.1471	.2305	.3138	.3971	.4805	.5638	.6471	.7305	.8138	.8971	.9805
				25		.0651	.1484	.2318	.3151	.3984	.4818	.5651	.6484	.7318	.8151	.8984	.9818
					51	.0664	.1497	.2331	.3164	.3997	.4831	.5664	.6497	.7331	.8164	.8997	.9831
			13	26		.0677	.1510	.2344	.3177	.4010	.4844	.5677	.6510	.7344	.8177	.9010	.9844
					53	.0690	.1523	.2357	.3190	.4023	.4857	.5690	.6523	.7357	.8190	.9023	.9857
				27		.0703	.1536	.2370	.3203	.4036	.4870	.5703	.6536	.7370	.8203	9036	.9870
					55	.0716	.1549	.2383	.3216	.4049	.4883	.5716	.6549	.7383	.8216	.9049	.9883
		7	14	28		.0729	.1563	.2396	.3229	.4063	.4896	.5729	.6563	.7396	.8229	9063	.9896
					57	.0742	.1576	.2409	.3242	.4076	.4909	.5742	.6576	.7409	.8242	.9076	.9909
				29		.0755	.1589	.2422	.3255	.4089	4922	.5755	.6589	.7422	.8255	9089	.9922
					59	.0768	.1602	.2435	.3268	.4102	4935	.5768	.6602	.7435	.8268	.9102	.9935
			15	30		.0781	.1615	.2448	.3281	.4115	.4948	.5781	6615	7448	8281	9115	.9948
					61	.0794	.1628	.2461	.3294	4128	.4961	.5794	6628	7461	8294	9128	9961
				31		0807	.1641	.2474	.3307	.4141	.4974	.5807	.6641	7474	.8307	.9141	.9974
					63	.0820	1654	.2487	.3320	4154	4987	5820	.6654	.7487	.8320	9154	.9987

TABLE 6

CONVERSION OF INCHES TO MILLIMETERS

Inches		0	1	2	3	4	5	6	7	8	9	10	11	12
		mm.	25.400	50.800	76.200	101.600	127.000	152.400	177.800	203.200	228.600	254.000	279.400	304.800
1/64	.015625	0.397	25.797	51.197	76.597	101.997	127.397	152.797	178.197	203.597	228.997	254.397	279.797	305.197
1/32	.03125	0.794	26.194	51.594	76.994	102.394	127.794	153.194	178.594	203.994	229.394	254.794	280.194	305.594
1/16	.0625	1.588	26.988	52.388	77.788	103.188	128.588	153.988	179.388	204.788	230.188	255.588	280.988	306.388
3/32	.09375	2.381	27.781	53.181	78.581	103.981	129.381	154.781	180.181	205.581	230.981	256.381	281.781	307.181
1/8	.125	3.175	28.575	53.975	79.375	104.775	130.175	155.575	180.975	206.375	231.775	257.175	282.575	307.975
5/32	.15625	3.969	29.369	54.769	80.169	105.569	130.969	156.369	181.769	207.169	232.569	257.969	283.369	308.769
3/16	.1875	4.763	30.163	55.563	80.963	106.363	131.763	157.163	182.563	207.963	233.363	258.763	284.163	309.563
7/32	.21875	5.556	30.956	56.356	81.756	107.156	132.556	157.956	183.356	208.756	234.156	259.556	284.956	310.356
1/4	.25	6.350	31.750	57.150	82.550	107.950	133.350	158.750	184.150	209.550	234.950	260.350	285.750	311.150
9/32	.28125	7.144	32.544	57.944	83.344	108.744	134.144	159.544	184.944	210.344	235.744	261.144	286.544	311.944
5/16	.3125	7.938	33.338	58.738	84.138	109.538	134.938	160.338	185.738	211.138	236.538	261.938	287.338	312.738
11/32	.34375	8.731	34.131	59.531	84.931	110.331	135.731	161.131	186.531	211.931	237.331	262.731	288.131	313.531
3/8	.375	9.525	34.925	60.325	85.725	111.125	136.525	161.925	187.325	212.725	238.125	263.525	288.925	314.325
13/32	.40625	10.319	35.719	61.119	86.519	111.919	137.319	162.719	188.119	213.519	238.919	264.319	289.719	315.119
7/16	.4375	11.113	36.513	61.913	87.313	112.713	138.113	163.513	188.913	214.313	239.713	265.113	290.513	315.913
15/32	.46875	11.906	37.306	62.706	88.106	113.506	138.906	164.306	189.706	215.106	240.506	265.906	291.306	316.706
1/2	.50	12.700	38.100	63.500	88.900	114.300	139.700	165.100	190.500	215.900	241.300	266.700	292.100	317.500
17/32	.53125	13.494	38.894	64.294	89.694	115.094	140.494	165.894	191.294	216.694	242.094	267.494	292.894	318.294
9/16	.5625	14.288	39.688	65.088	90.488	115.888	141.288	166.688	192.088	217.488	242.888	268.288	293.688	319.088
19/32	.59375	15.081	40.481	65.881	91.281	116.681	142.081	167.481	192.881	218.281	243.681	269.081	294.481	319.881
5/8	.625	15.875	41.275	66.675	92.075	117.475	142.875	168.275	193.675	219.075	244.475	269.875	295.275	320.675
21/32	.65625	16.669	42.069	67.469	92.869	118.269	143.669	169.069	194.469	219.869	245.269	270.669	296.069	321.469
11/16	.6875	17.463	42.863	68.263	93.663	119.063	144.463	169.863	195.263	220.663	246.063	271.463	296.863	322.263
23/32	.71875	18.256	43.656	69.056	94.456	119.856	145.256	170.656	196.056	221.456	246.856	272.256	297.656	323.056
3/4	.75	19.050	44.450	69.850	95.250	120.650	146.050	171.450	196.850	222.250	247.650	273.050	298.450	323.850
25/32	.78125	19.844	45.244	70.644	96.044	121.444	146.844	172.244	197.644	223.044	248.444	273.844	299.244	324.644
13/16	.8125	20.638	46.038	71.438	96.838	122.238	147.638	173.038	198.438	223.838	249.238	274.638	300.038	325.438
27/32	.84375	21.431	46.831	72.231	97.631	123.031	148.431	173.831	199.231	224.631	250.031	275.431	300.831	326.231
7/8	.875	22.225	47.625	73.025	98.425	123.825	149.225	174.625	200.025	225.425	250.825	276.225	301.625	327.025
29/32	.90625	23.019	48.419	73.819	99.219	124.619	150.019	175.419	200.819	226.219	251.619	277.019	302.419	327.819
15/16	.9375	23.813	49.213	74.613	100.013	125.413	150.813	176.213	201.613	227.013	252.413	277.813	303.213	328.613
31/32	.96875	24.606	50.006	75.406	100.806	126.206	151.606	177.006	202.406	227.806	253.206	278.606	304.006	329.406

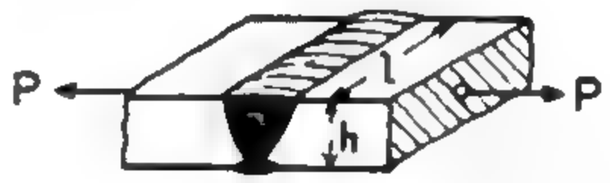
TABLE 7

COMPARISON OF GAGES, IN.

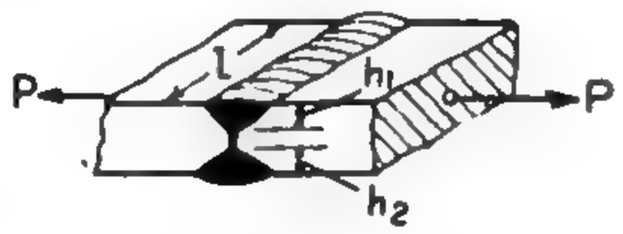
Gage No.	American or B. & S.	Birmingham or Stubs	U. S. Steel Wire	United States Standard
0000000	.....	...	0.4900	0.5000
000000	0.5800	...	0.4615	0.4688
00000	0.5165	...	0.4305	0.4375
0000	0.4600	0.454	0.3938	0.4063
000	0.4096	0.425	0.3625	0.3750
00	0.3648	0.380	0.3310	0.3438
0	0.3249	0.340	0.3065	0.3125
1	0.2893	0.300	0.2830	0.2813
2	0.2576	0.284	0.2625	0.2656
3	0.2294	0.259	0.2437	0.2500
4	0.2043	0.238	0.2253	0.2344
5	0.1819	0.220	0.2070	0.2188
6	0.1620	0.203	0.1920	0.2031
7	0.1443	0.180	0.1770	0.1875
8	0.1285	0.165	0.1620	0.1719
9	0.1144	0.148	0.1483	0.1563
10	0.1019	0.134	0.1350	0.1406
11	0.0907	0.120	0.1205	0.1250
12	0.0808	0.109	0.1055	0.1094
13	0.0720	0.095	0.0915	0.0938
14	0.0641	0.083	0.0800	0.0781
15	0.0571	0.072	0.0720	0.0730
16	0.0508	0.065	0.0625	0.0625
17	0.0453	0.058	0.0540	0.0563
18	0.0403	0.049	0.0475	0.0500
19	0.0359	0.042	0.0410	0.0438
20	0.0320	0.035	0.0348	0.0375
21	0.0285	0.032	0.0317	0.0344
22	0.0524	0.028	0.0286	0.0313
23	0.0226	0.025	0.0258	0.0281
24	0.0201	0.022	0.0230	0.0250
25	0.0179	0.020	0.0204	0.0219
26	0.0159	0.018	0.0181	0.0188
27	0.0142	0.016	0.0173	0.0172
28	0.0126	0.014	0.0162	0.0156
29	0.0113	0.013	0.0150	0.0141
30	0.0100	0.012	0.0140	0.0125
31	0.0089	0.010	0.0132	0.0109
32	0.0080	0.009	0.0128	0.0102
33	0.0071	0.008	0.0118	0.0094
34	0.0063	0.007	0.0104	0.0086
35	0.0056	0.005	0.0095	0.0078
36	0.0050	0.004	0.0090	0.0070
37	0.0045	...	0.0085	0.0066
38	0.0040	...	0.0080	0.0063
39	0.0035	...	0.0075	....
40	0.0031	...	0.0070	....
41	0.0028	...	0.0066	....
42	0.0025	...	0.0062	....
43	0.0022	...	0.0060	....
44	0.0020	...	0.0058	....
45	0.0018	...	0.0055	....
46	0.0016	...	0.0052	....
47	0.0014	...	0.0050	....
48	0.0012	...	0.0048	....
49	0.0011	...	0.0046	....
50	0.0010	...	0.0044	....

TABLE 8

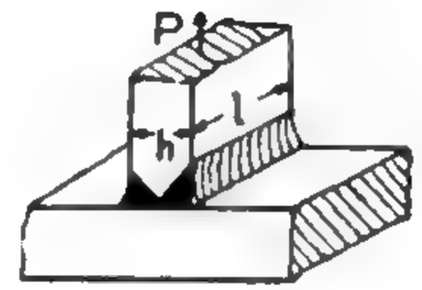
WELD STRESS FORMULAS



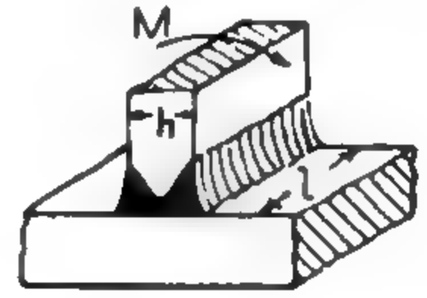
$$S = \frac{P}{hl}$$



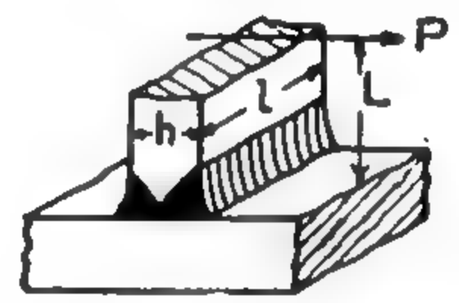
$$S = \frac{P}{(h_1+h_2)l}$$



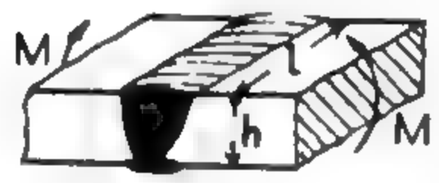
$$S = \frac{P}{hl}$$



$$S = \frac{6M}{lh^2}$$

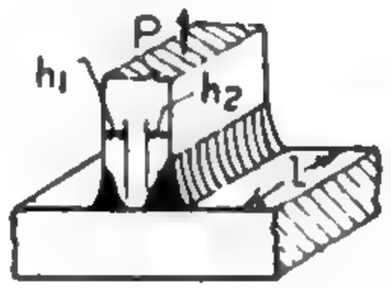


$$S = \frac{6PL}{lh^2} \qquad S_s = \frac{P}{lh}$$

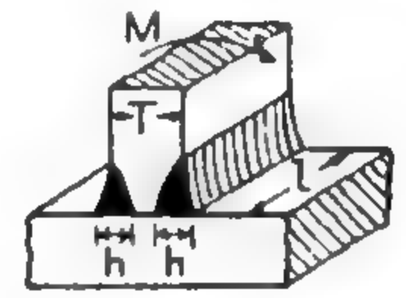


$$S = \frac{6M}{lh^2}$$

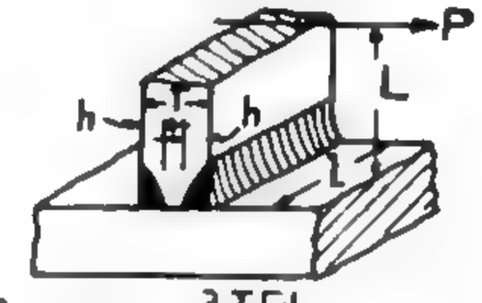
$$S = \frac{3TM}{lh(3T^2-6Th+4h^2)}$$



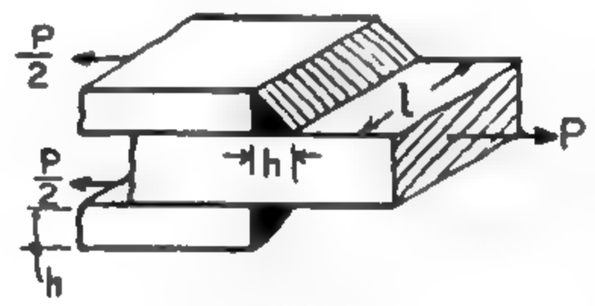
$$S = \frac{P}{(h_1+h_2)l}$$



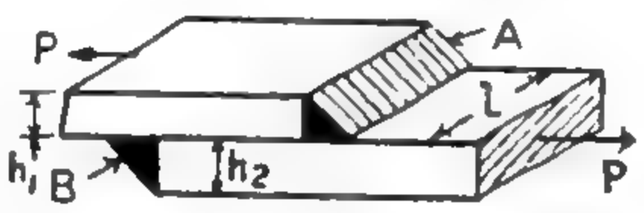
$$S = \frac{3TM}{lh(3T^2-6Th+4h^2)}$$



$$S = \frac{3TPL}{lh(3T^2-6Th+4h^2)} \qquad S_s = \frac{P}{2lh}$$

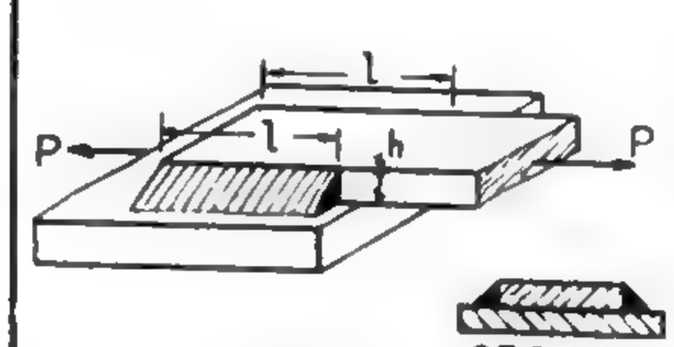


$$S = \frac{.707\,P}{hl}$$

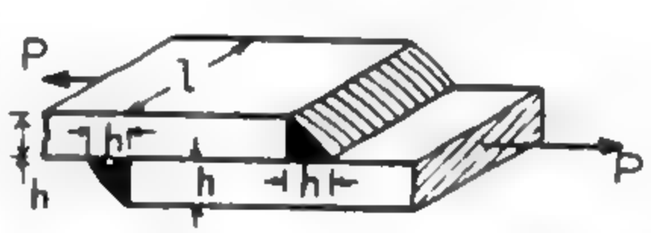


STRESS IN WELD A EQUALS STRESS IN WELD B

$$S = \frac{1.414\,P}{(h_1+h_2)l}$$

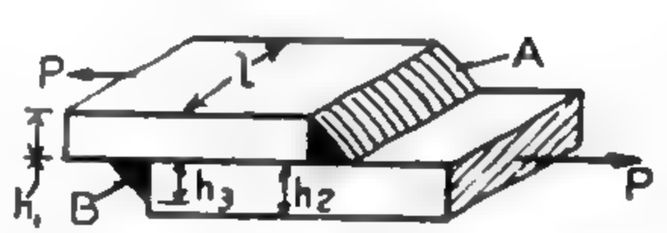


$$S = \frac{.707\,P}{hl}$$



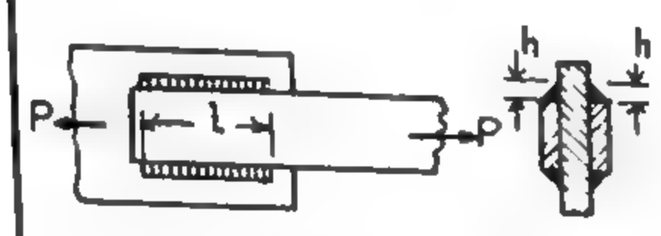
BOTH PLATES SAME THICKNESS

$$S = \frac{.707\,P}{hl}$$

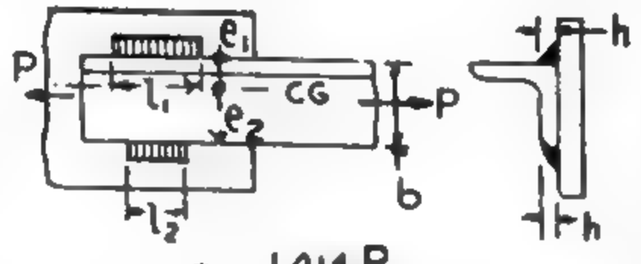


WELD A $S = \frac{1.414\,P}{(h_1+h_2)l}$

WELD B $S = \frac{1.414\,Ph_2}{h_3 l\,(h_1+h_2)}$

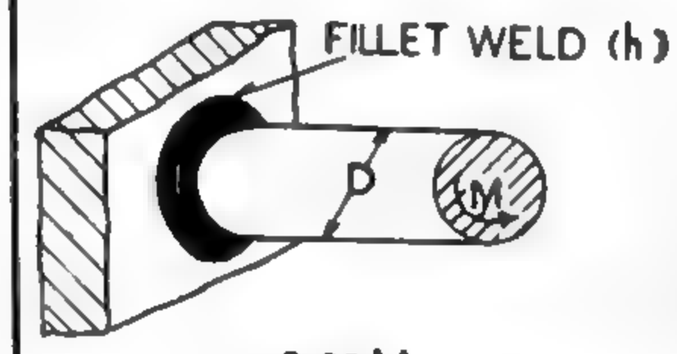


$$S = \frac{.354\,P}{hl}$$

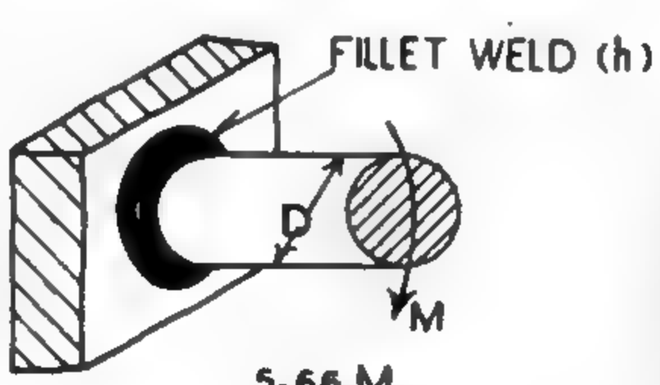


$$S = \frac{1.414\,P}{h(l_1+l_2)} \text{ OR}$$

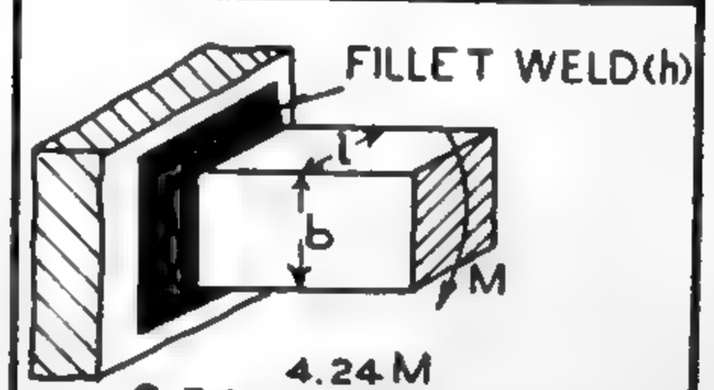
$$l_1 = \frac{1.414\,Pe_2}{Shb}\,; \quad l_2 = \frac{1.414\,Pe_1}{Shb}$$



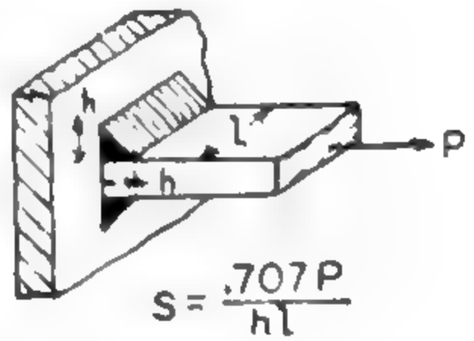
$$S_s = \frac{2.83\,M}{hD^2\pi}$$



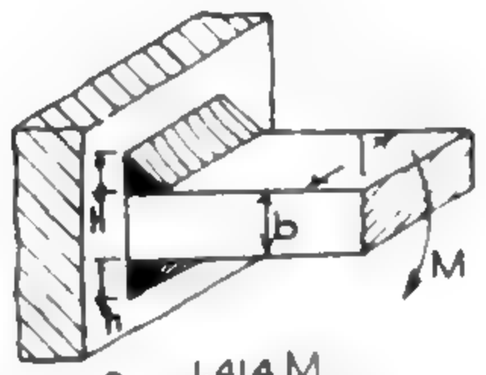
$$S = \frac{5.66\,M}{hD^2\pi}$$



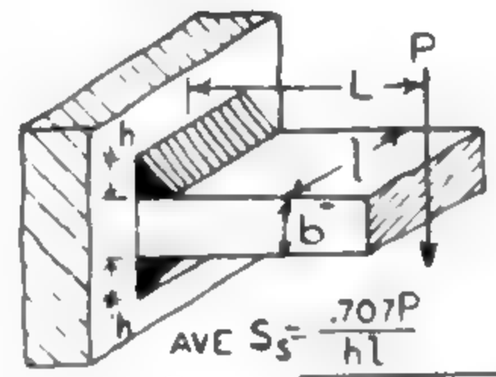
$$S = \frac{4.24\,M}{h[b^2+3l(b+h)]}$$



$$S = \frac{.707P}{hl}$$

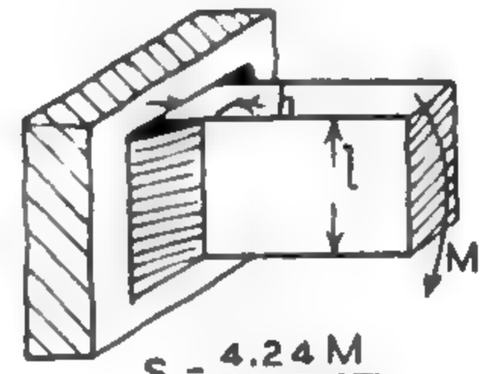


$$S = \frac{1.414M}{hl(b+h)}$$

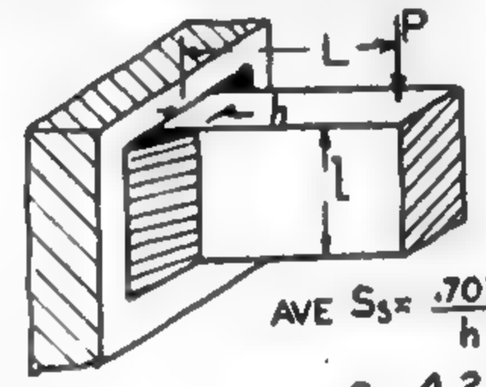


$$\text{AVE } S_S = \frac{.707P}{hl}$$

$$\text{MAX } S = \frac{P}{hl(b+h)}\sqrt{2L^2+\frac{(b+h)^2}{2}}$$

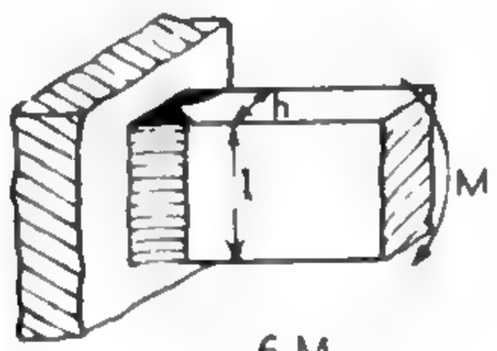


$$S = \frac{4.24M}{hl^2}$$

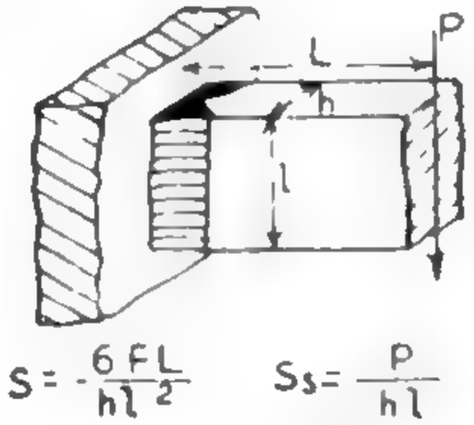


$$\text{AVE } S_S = \frac{.707P}{hl}$$

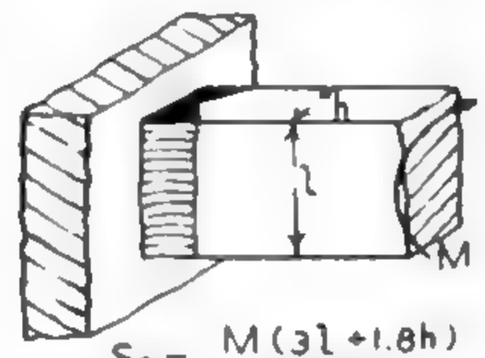
$$\text{MAX } S = \frac{4.24PL}{hl^2}$$



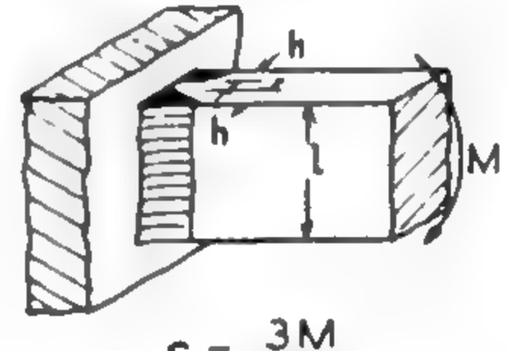
$$S = \frac{6M}{hl^2}$$



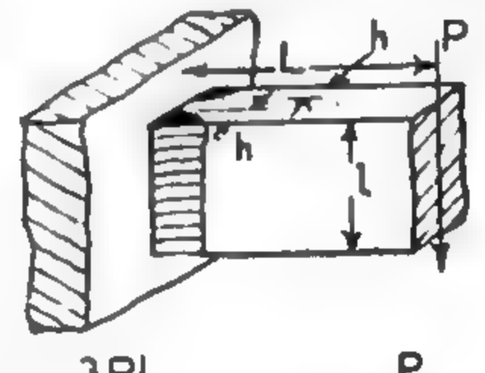
$$S = \frac{6FL}{hl^2} \qquad S_S = \frac{P}{hl}$$



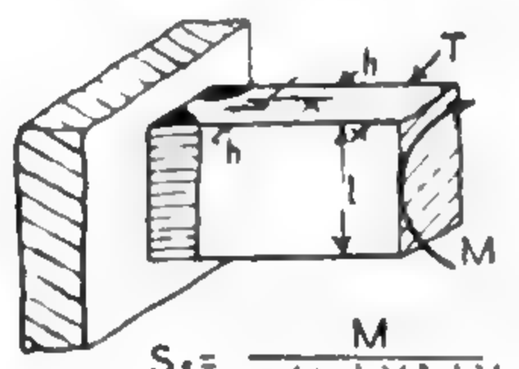
$$S_S = \frac{M(3l+1.8h)}{h^2l^2}$$



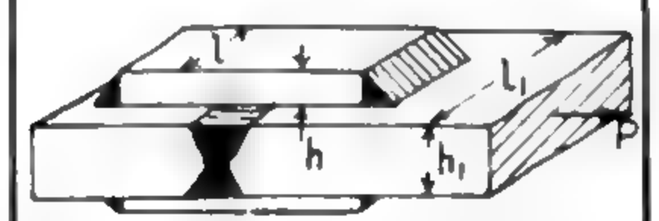
$$S = \frac{3M}{hl^2}$$



$$S = \frac{3PL}{hl^2} \qquad S_S = \frac{P}{2hl}$$



$$S_S = \frac{M}{2(T-h)(l-h)h}$$

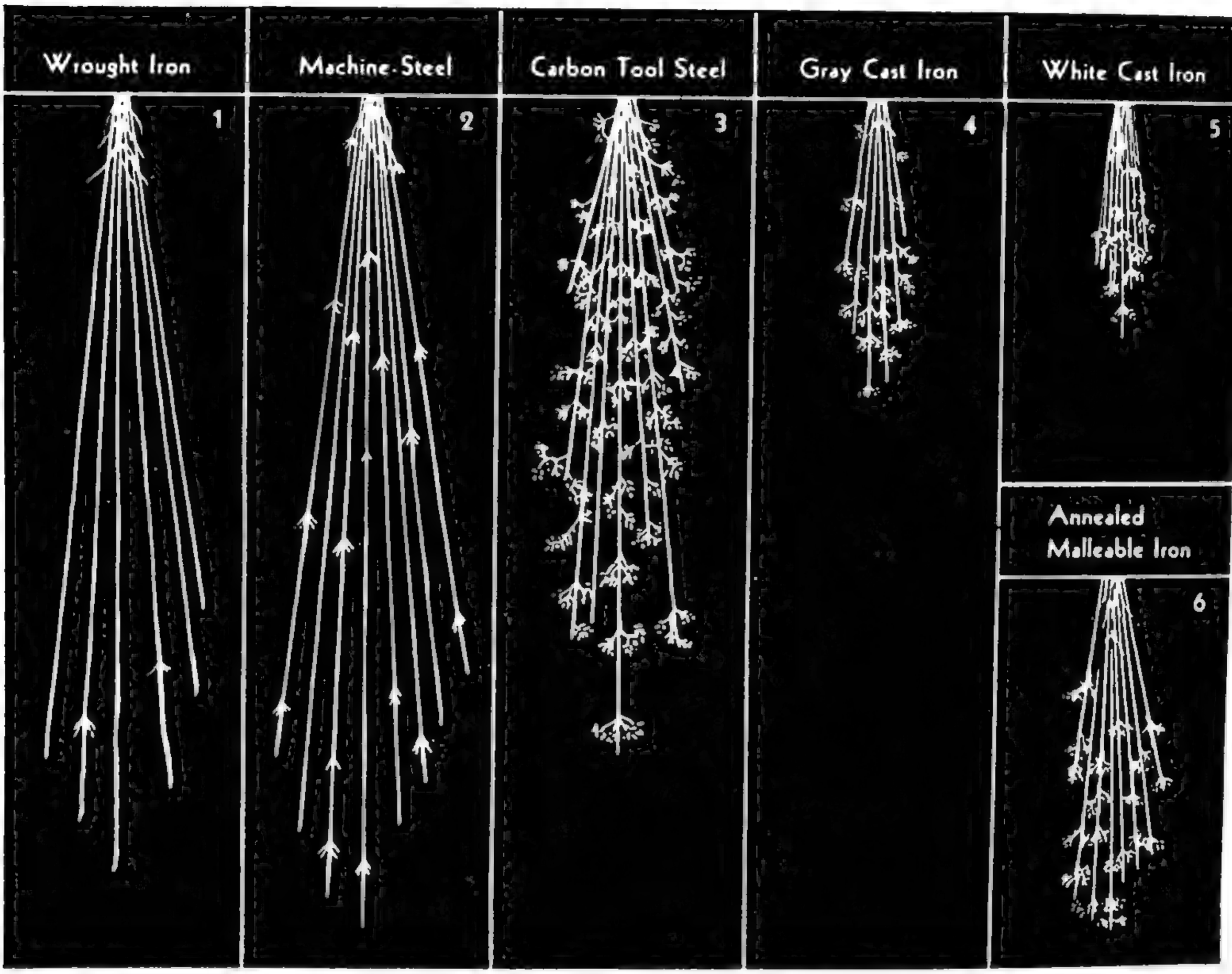


$$\text{FILLET WELD, } S = \frac{1.414P}{2hl+h_1l_1}$$

$$\text{BUTT WELD, } S = \frac{P}{2hl+h_1l_1}$$

S = Normal stress, psi.
Ss = Unit stress, psi.
I = Moment of inertia, in. units
M = Bending moment, in lb.
D = External load, lb.
L = Linear distance
H = Size of weld
l = Length of weld, in.

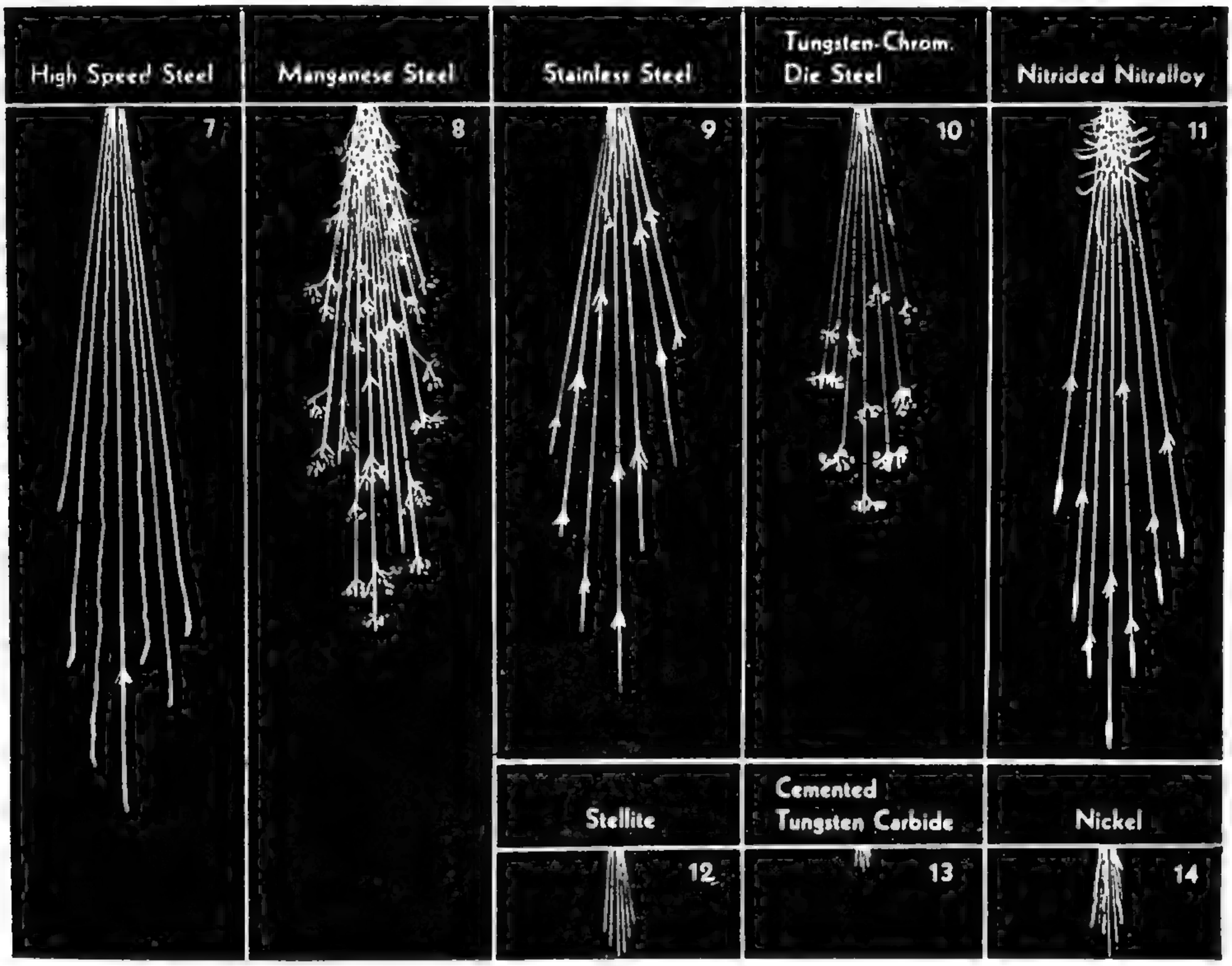
TABLE 9



	Metal	Volume of Stream	Relative Length of Stream, Inches†
1.	Wrought iron	Large	65
2.	Machine steel	Large	70
3.	Carbon tool steel	Moderately large	55
4.	Gray cast iron	Small	25
5.	White cast iron	Very small	20
6.	Annealed mall. iron	Moderate	30
7.	High speed steel	Small	60
8.	Manganese steel	Moderately large	45
9.	Stainless steel	Moderate	50
10.	Tungsten-chromium die steel	Small	35
11.	Nitrided Nitralloy	Large (curved)	55
12.	Stellite	Very small	10
13.	Cemented tungsten carbide	Extremely small	2
14.	Nickel	Very small**	10
15.	Copper, brass, aluminum	None	

† Figures obtained with 12" wheel on bench stand and are relative only. Actual length in each instance will vary with grinding wheel pressure, etc.

IDENTIFICATION OF METALS BY SPARKS



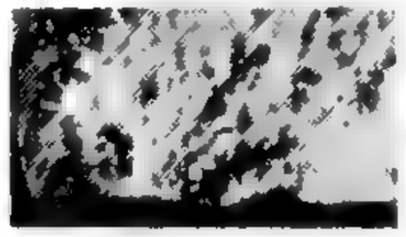
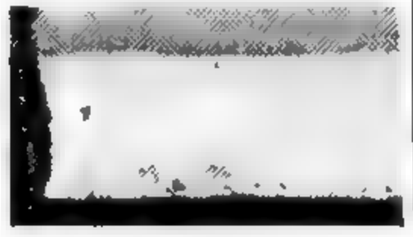
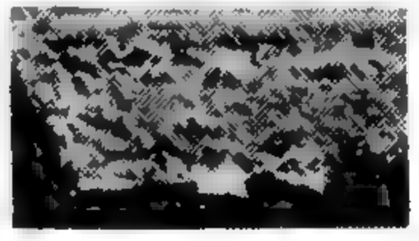
Color of Stream Close to Wheel	Color of Streaks Near End of Stream	Quantity of Spurts	Nature of Spurts	
Straw	White	Very few	Forked	1.
White	White	Few	Forked	2.
White	White	Very many	Fine, repeating	3.
Red	Straw	Many	Fine, repeating	1.
Red	Straw	Few	Fine, repeating	5.
Red	Straw	Many	Fine, repeating	6.
Red	Straw	Extremely few	Forked	7.
White	White	Many	Fine, repeating	8.
Straw	White	Moderate	Forked	9.
Red	Straw*	Many	Fine, repeating	10.
White	White	Moderate	Forked	11.
Orange	Orange	None		12.
Light Orange	Light Orange	None		13.
Orange	Orange	None		14.
		None		15.

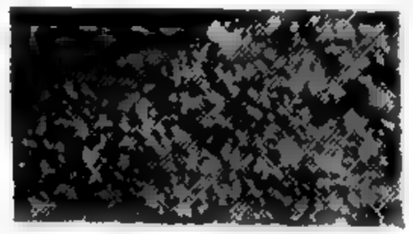
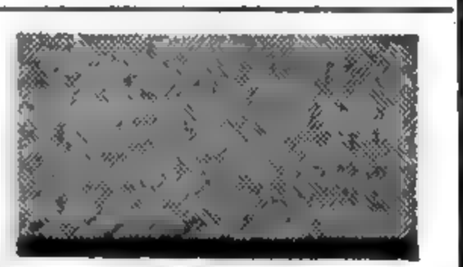
*Blue-white spurts. **Some wavy streaks

TABLE 10

METAL IDENTIFICATION BY FRACTURE OR CHIP

A—Identification of Metals by Appearance

	ALLOY*‡ STEEL	COPPER	BRASS AND BRONZE	ALUMINUM AND ALLOYS†	MONEL METAL	NICKEL	LEAD††
FRACTURE	medium gray	red color	 red to yellow	 white	light gray	 almost white	white; crystalline
UNFINISHED SURFACE	Dark gray; relatively rough; rolling or forging lines may be noticeable	Various degrees of reddish brown to green due to oxides; smooth	Various shades of green, brown, or yellow due to oxides; smooth	Evidences of mold or rolls; very light gray	Smooth; dark gray	Smooth; dark gray	Smooth; velvety; white to gray
NEWLY MACHINED	Very smooth; bright gray	Bright copper red color dulls with time	Red through to whitish yellow; very smooth	Smooth; very white	Very smooth; light gray	Very smooth; white	Very smooth; white

	WHITE CAST IRON°	GRAY CAST IRON	MALLEABLE* IRON	WROUGHT IRON	LOW-CARBON STEEL AND CAST STEEL	HIGH-CARBON STEEL
FRACTURE	Very fine silvery white silky crystalline formation	 dark gray	dark gray	bright gray	bright gray	 very light gray
UNFINISHED SURFACE	Evidence of sand mold; dull gray	Evidence of sand mold; very dull gray	Evidence of sand mold; dull gray	Light gray; smooth	Dark gray; forging marks may be noticeable; cast—evidences of mold	Dark gray; rolling or forging lines may be noticeable
NEWLY MACHINED	Rarely machined	Fairly smooth; light gray	Smooth surface; light gray	Very smooth surface; light gray	Very smooth; bright gray	Very smooth; bright gray

B—Identification of Metals by Chips

	ALLOY** STEEL	COPPER	BRASS AND BRONZE	ALUMINUM AND ALLOYS†	MONEL METAL	NICKEL	LEAD††
APPEARANCE OF CHIP	**	Smooth chips; saw edges where cut	Smooth chips; saw edges where cut	Smooth chips; saw edges where cut	Smooth edges	Smooth edges	Any shaped chip can be secured because of softness
SIZE OF CHIP	**	Can be continuous if desired	Can be continuous if desired	Can be continuous if desired	Can be continuous if desired	Can be continuous if desired	Can be continuous if desired
FACILITY OF CHIPPING	**	Very easily cut	Easily cut; more brittle than copper	Very easily cut	Chips easily	Chips easily	Chips so easily it can be cut with penknife

	WHITE CAST IRON°	GRAY CAST IRON	MALLEABLE* IRON	WROUGHT IRON	LOW-CARBON STEEL AND CAST STEEL	HIGH-CARBON STEEL
APPEARANCE OF CHIP	Small broken fragments	Small partially broken chips but possible to chip a fairly smooth groove	Chips do not break short as in cast iron	Smooth edges where cut	Smooth edges where cut	Fine grain fracture; edges lighter in color than low-carbon steel
SIZE OF CHIP		1/8 in.	1/4–3/8 in.	Can be continuous if desired	Can be continuous if desired	Can be continuous if desired
FACILITY OF CHIPPING	Brittleness prevents chipping a path with smooth sides	Not easy to chip because chips break off from base metal	Very tough, therefore harder to chip than cast iron	Soft and easily cut or chipped	Easily cut or chipped	Metal is usually very hard, but can be chipped

See footnotes at end of table.

10C—Identification of Metals by Flame Test

	ALLOY** STEEL	COPPER	BRASS AND BRONZE	ALUMINUM AND ALLOYS†	MONEL METAL	NICKEL	LEAD††
SPEED OF MELTING (From Cold State)	**	Slow	Moderate to fast	Faster than steel	Slower than steel	Slower than steel	Very fast
COLOR CHANGE WHILE HEATING	**	May turn black and then red; copper color may become more intense	Becomes noticeably red before melting	No apparent change in color	Becomes red before melting	Becomes red before melting	No apparent change
APPEARANCE OF SLAG	**	So little slag that it is hardly noticeable	Various quantities of white fumes, though bronze may not have any	Stiff black scum	Gray scum; considerable amounts	Gray scum; less slag than Monel Metal	Dull gray coating
ACTION OF SLAG	**	Quiet	Appears as fumes	Quiet	Quiet; hard to break	Quiet; hard to break	Quiet
APPEARANCE OF MOLTEN PUDDLE	**	Has mirrorlike surface directly under flame	Liquid	Same color as unheated metal; very fluid under slag	Fluid under slag	Fluid under slag film	White and fluid under slag
ACTION OF MOLTEN PUDDLE UNDER BLOWPIPE FLAME	**	Tendency to bubble; puddle solidifies slowly and may sink slightly	Like drops of water; with oxidizing flame will bubble	Quiet	Quiet	Quiet	Quiet; may boil if too hot

10C (Continued)—Identification of Metals by Flame Test

	WHITE CAST IRON°	GRAY CAST IRON	MALLEABLE* IRON	WROUGHT IRON	LOW-CARBON STEEL AND CAST STEEL	HIGH-CARBON STEEL
SPEED OF MELTING (From Cold State)	Moderate	Moderate	Moderate	Fast	Fast	Fast
COLOR CHANGE WHILE HEATING	Becomes dull red before melting	Becomes dull red before melting	Becomes red before melting	Becomes bright red before melting	Becomes bright red before melting	Becomes bright red before melting
APPEARANCE OF SLAG	A medium film develops	A thick film develops	A medium film develops	Oily or greasy appearance with white lines	Similar to molten metal	Similar to molten metal
ACTION OF SLAG	Quiet; tough, but can be broken up	Quiet; tough, but possible to break it up	Quiet; tough, but can be broken	Quiet; easily broken up	Quiet	Quiet
APPEARANCE OF MOLTEN PUDDLE	Fluid and watery; reddish white	Fluid and watery; reddish white	Fluid and watery; straw color	Liquid; straw color	Liquid; straw color	Lighter than low-carbon steel; has a cellular appearance
ACTION OF MOLTEN PUDDLE UNDER BLOWPIPE FLAME	Quiet; no sparks; depression under flame disappears when flame is removed	Quiet; no sparks; depression under flame disappears when flame is removed	Boils and leaves blowholes; surface metal sparks; interior does not	Does not get viscous; generally quiet; may be slight tendency to spark	Molten metal sparks	Sparks more freely than low-carbon steel

° Very seldom used commercially.
* Malleable iron should always be bronze-welded.
** Alloy steels vary so much in composition and consequently in results of tests that experience is the best solution to identification problems.
† Due to white or light color and extremely light weight, aluminum is usually easily distinguishable from all other metals; aluminum alloys are usually harder and slightly darker in color than pure aluminum.
†† Weight, softness, and great ductility are distinguishing characteristics of lead.

TABLE 11

GENERAL PROPERTIES OF METALS AND ALLOYS

Metal or Alloy	Melting Point, °F.	Linear expansion, (In./Ft./°F.) × 10^{-3}	Heat Conductivity, Btu./Hr./Sq.Ft./In./°F.	Weight, Lb./Cu. In.	Shrinkage Allowance in Castings, In./Ft.	Brinell Hardness Hard	Brinell Hardness Soft	Tensile Strength, Psi. × 1000	Manufactured by	Chemical Composition, % (Approx.)
Allegheny Metal	2640	0.115	...	0.283	....	..	140	90–120[a]	Allegheny Steel	.....
Aluminum—Cast—8% Copper	1175	...	....	....	0.1875	..	...	20	.....	Al 92, Cu 8
Aluminum—Pure	1218	0.148	1393	0.096	....	40	33	12–28	.....	Al
Aluminum—5% Silicon	1117	0.146	...	0.093	....	..	...	18	Alum. Co. of America	Al 95, Si 5
Ambrac A	2100	0.109	...	0.310	....	..	...	50–130	American Brass	Cu 75, Ni 20, Zn 5
Antimony	1166	0.075	...	0.245	....	..	...	1	.....	Sb
Bismuth	520	...	...	....	....	..	...	...	.....	Bi
Boron	3992	...	...	0.094	....	..	...	...	.....	B
Brass—Commercial High	1660	0.115	756	0.306	0.1875	..	...	46	.....	Cu 66, Zn 34
Bronze—Tobin	1625	0.119	...	0.304	....	..	...	54	.....	Cu 60, Zn 39, Sn 1
Bronze—Muntz Metal	1625	...	...	....	....	..	...	...	.....	Cu 60, Zn 40
Bronze—Manganese	1598	0.119	...	0.302	....	..	95	60	.....	.....
Bronze—Phosphor	1922	0.119	...	0.321	....	160	100	45	.....	Cu 96, Sn 3.75, P 0.25
Cadmium	610	...	...	....	....	..	...	...	.....	Cd
Carbon	6332[b]	...	...	....	....	..	...	...	.....	C
Chromium	2740	...	...	0.235	....	..	...	...	.....	Cr
Cobalt	2700	0.082	...	0.312	....	..	...	34.4	.....	Co
Copper—Deoxidized	1981	0.118	...	0.307	0.25	..	...	32–55	.....	Cu 99.99
Copper—Electrolytic	1981	0.106	2640	0.322	....	107	42	20–70	.....	Cu 99.93, O 0.07
Duriron[c]	2310	0.104	...	0.253	0.1875	..	...	...	Duriron	Si 14.5, C 0.85, Mn 0.35, Fe bal.
Everdur	1866	0.113	871	0.306	0.1875	180	80	52–100	American Brass	Cu 94.8–96, Si 3–4, Mn 1–1.2
Gold	1945	0.094	2046	0.697	....	..	...	14	.....	Au
Iron—Cast	2300	0.067	338	0.260[d]	0.125	250	193	15	.....	C 2.80–3.40, Si Mn, P, S, Fe bal.
Iron—Malleable	2300	...	...	0.268	0.125	..	...	53	.....	C 1.75–2.80, Si, Mn, P, S, Fe bal.
Iron—Pure	2786	0.078	467	0.283	....	..	84	38.5	.....	Fe

Iron—Wrought	2900	0 078	419	0.278	...	..	90	48	.....	Fe and Slag
Lead—Pure	620	0.181	240	0.411	0.312	..	6	1.78	.....	Pb
Lead—Chemical	620	0.193	...	0.410	0 312	.	...	1.78	.....	Pb 99.92, Cu 0.08
Manganal	2450	...	...	....	...	.	..	...	Stulz-Sickles	C 0.60–0.85, Mn 11.0–13.5, Ni 2.50–3.50, Si 0.60–0.95, Fe, bal.[e]
Manganese	2246	...	...	0.268	....	..	...	...	.....	Mn
Molybdenum	4532	...	100	0.309	....		..	42.5–154	.....	Mo
Monel	2480	0 093	174	0.318	....	190	105	79–109[f]	International Nickel	Ni 67, Cu 28, Fe, Mn, Si, C, S bal.
Nichrome	2460	0.091	...	0 295	....	..	...	100	Driver-Harris	Ni 60, Fe 24, Cr 16, C 0.1
Nickel	2646	0.083	413	0.319	0.25	..	112	61–109[f]	.....	Ni
Nickel Silver—18%	1955	0.122	...	0 309	..	158	77	58–95	.....	Cu 65, Ni 18, Zn 17
Platinum	3218	...	...	....	....	..	65	...	.....	Pt
Silicon	2588	...	...	....	....	..	...	...	.....	Si
Silfram	...	...	...	....	....	437	...	...	Stoody	Cr 31.75, Ni 10, C 2, Si 4.75, Fe[e]
Sil-Fos	1300	...	..	...	..	..	...	33[g]	Handy & Harman	Ag 15, Cu 80, P 5[e]
Silver— Pure	1762	0 126	2919	0 380	...	..	65	36	.....	Ag
Steel—Hard (0.40–0.70% Carbon)	2500	0.076	312[h]	0.283	....	590	240	75	.....	.....
Steel—Low-Carbon (0.15% max.)	2700	0.076	...	0.283	....	..	138	50	.....	.....
Steel—Medium (0.15–0.40% Carbon)	2600	0.076	...	0.283	....	..	180	60	.....	.....
Steel—Manganese	2450	...	...	....	....	255	...	70–100	.....	C 1.0–1.45, Mn 12–15, Si 0.10–0.20, Fe bal.
Steel—Amsco Nickel Manganese	2450	...	...	....	....	..	...	...	American Manganese	C 1.3, Mn 14, Ni 5, Si 0.35, Fe bal.[e]
Steel—Nickel—3½%	2600	...	.	0 284	.. .	..	...	80	.....	Ni 3.25–3.75, C 0.15–0.25, Mn 0.50 0.80
Steel—Cast	2600	..	...	0 282	0 25	..	144	58	.....	.....
Stainless Steel—18-8	2550	0 073	...	0 279	....	..	140	89–100	.....	Cr 18, Ni 8, C 0.16, Fe bal.
Stainless Steel—18-8 Low-Carbon	2640	..	...	0 280	....	.	140	80[a]	.....	Cr 18, Ni 8, C 0.07, Fe bal.
Stellite	2305	0 105	...	0.307	....	532	...	47–105	Haynes Stellite	Co 43–55, W 11–14, Cr 25–34
Stoody Self-Hardening Metal	...	...	...	...	....	495	...	...	Stoody	Cr 7, Mn 4, C 1.0, Si 1.25, Fe 86.75
Stoodite	..	...	...	....	....	578	...	...	Stoody	Cr 29 5, Mn 8, C 2, Si 2, Fe 58.5[e]
Tin	450	0.139	450	0.263	0 083	..	15	5	.....	Sn
Timang	2450	...	...	....	....	..	...	...	Taylor-Wharton	.....
Tungsten	6152	...	1381	0.678	....	..	442	...	.....	W
Tungsten Carbide	...[j]	...	...	....	....	9[k]	...	...	.....	.....
Vanadium	3182	...	...	0.199	..	..	.	...	.....	V
Zinc—Cast	786	0.169	...	0.248	0.312	..	45	9	.....	Zn
Zinc—Rolled	786	0.169	770	0.258	....	..	. .	31[l]	.....	Zn

[a] Annealed.
[b] Greater than.
[c] Acid-resisting iron.
[d] 0.260–0.290 lb./cu. in.
[e] Welding rods.
[f] Sheets—from *soft* to *full hard*.
[g] Joint strength.
[h] 1 % carbon.
[i] Cannot be melted with torch.
[k] Moh's scale.
[l] Average hard-rolled.

TABLE 12

ELEMENTS AND THEIR PROPERTIES

Element	Symbol	Density Lb./Cu. In. at 68°F.	Melting Point, °F.
Actinium	Ac	....	1600.0
Aluminum	Al	0.0975	1220.4
Americium	Am	....	....
Antimony	Sb	0.2391	1166.9
Argon	A	1.663×10^{-3}	308.9
Arsenic	As	0.2070	1497.0
Astatine	At	....	....
Barium	Ba	0.1265	1562
Beryllium	Be	0.0658	2345
Bismuth	Bi	0.3541	519
Boron	B	0.083	4200
Bromine	Br	0.113	19.0
Cadium	Cd	0.3125	609.6
Calcium	Ca	0.0560	1560
Carbon	C	0.0802	6700
Cerium	Ce	0.25	1100
Cesium	Cs	0.069	82
Chlorine	Cl	....	−150
Chromium	Cr	0.2579	3430
Cobalt	Co	0.3216	2723
Columbium	Cb	0.3096	4380
Copper	Cu	0.324	1981.4
Curium	Cm	....	....
Dysprosium	Dy	0.309	....
Erbium	Er	0.331	....
Europium	Eu	0.189	....
Fluorine	F	....	−370
Francium	Fa	....	....
Gadolinium	Gd	0.287	....
Gallium	Ga	0.214	85.60
Germanium	Ge	0.194	1760
Gold	Au	0.698	1945.4
Hafnium	Hf	0.412	3100
Helium	He	0.6012×10^{-5}	456.5
Holmium	Ho	....	....
Hydrogen	H	0.3026×10^{-5}	−434.6
Illinium	Il	....	....
Indium	In	0.264	313.5
Iodine	I	0.178	237
Iridium	Ir	0.813	4449
Iron	Fe	0.284	2802
Krypton	Kr	0.126×10^{-3}	−251
Lanthanum	La	0.222	1519
Lead	Pb	0.4097	621.3
Lithium	Li	0.019	367
Lutecium	Lu	0.352	....
Magnesium	Mg	0.0628	1202
Manganese	Mn	0.268	2273
Mercury	Hg	0.4896	39.97
Molybdenum	Mo	0.369	4760
Neodymium	Nd	0.255	1540
Neon	Ne	3.03×10^{-5}	−415.5
Neptunium	Np	....	....
Nickel	Ni	0.322	2651
Nitrogen	N	4.209×10^{-5}	−346
Osmium	Os	0.813	4900
Oxygen	O	4.8118×10^{-5}	−361.8
Palladium	Pd	0.434	2829
Phosphorus	P	0.0658	111.4
Platinum	Pt	0.775	3224.3
Plutonium	Pu	....	....
Polonium	Po	....	1100
Potassium	K	0.031	145
Praseodymium	Pr	0.240	1700
Protoactinium	Pa	....	5400
Radium	Ra	0.18	1300
Radon	Rn	0.159	−96
Rhemium	Re	0.72	5740
Rhodium	Rh	0.4495	3571
Rubidium	Rb	0.0553	102
Ruthenium	Ru	0.441	4500
Samarium	Sm	0.28	2370
Scandium	Sc	0.090	2190
Selenium	Se	0.174	428
Silicon	Si	0.084	2605
Silver	Ag	0.3790	1760.9
Sodium	Na	0.035	207.9
Strontium	Sr	0.094	1420
Sulfur	S	0.075	246.2
Tantalum	Ta	0.600	5425
Technetium	Tc	....	4900
Tellurium	Te	0.225	840
Terbium	Tb	0.301	621
Thallium	Tl	0.4281	572
Thorium	Th	0.415	3300
Thulium	Tm	0.338	....
Tin	Sn	0.2637	449.4
Titanium	Ti	0.164	3300
Tungsten	W	0.698	6170
Uranium	U	0.676	2065
Vanadium	V	0.217	3150
Xenon	Xe	0.1985×10^{-3}	−170
Ytterbium	Yb	0.253	....
Yttrium	Y	0.199	2700
Zinc	Zn	0.258	787.03
Zirconium	Zr	0.23	3200

TABLE 13

EQUIVALENT VALUES OF ELECTRICAL, MECHANICAL AND HEAT UNITS

Unit	Equivalent Value in Other Units
1 Kilowatt-hour =	1000 whr. 1.341 hp.-hr. 2,655,200 ft.-lb. 3,600,000 joules 3415 Btu. 367,100 kg.-meters 0.234 lb. carbon oxidized with perfect efficiency 3.52 lb. water evap. from and at 212°F. 22.77 lb. water raised from 62 to 212°F.
1 Horsepower-hour =	0.7457 kw.-hr. 1,980,000 ft.-lb. 2546.5 Btu. 273,740 kg.-meters 0 174 lb. carbon oxidized with perfect efficiency 2.62 lb. water evap. from and at 212°F. 17.0 lb. water raised from 62 to 212°F.
1 Kilowatt =	1000 watts 1.3410 hp. 2,655,200 ft.-lb. per hr. 44,254 ft.-lb. per min. 737.56 ft.-lb. per sec. 3415 Btu. per hr. 56.92 Btu. per min. 0.9486 Btu. per sec. 0.234 lb. carbon oxidized per hr. 3.52 lb. water evap. per hr. from and at 212°F.
1 Horsepower =	745.7 watts 0.7457 kw. 33,000 ft.-lb. per min. 550 ft.-lb. per sec. 2546.5 Btu. per hr. 42.44 Btu. per min. 0.707 B.t.u. per sec. 0.174 lb. carbon oxidized per hr. with perfect efficiency 2.62 lb. water evap. per hour from and at 212°F.
1 Joule =	1 watt-sec. 0.000000278 kw.-hr. 0.10197 kg.-meter 0.0009486 Btu. 0.73756 ft.-lb.
1 Foot-pound =	1.3558 joules 0.13826 kg.-meter 0.0000003766 kw.-hr. 0.0012861 Btu. 0.0000005 hp.-hr.
1 Watt =	1 joule per sec. 0.001341 hp. 3.415 Btu. per hr. 0.73756 ft.-lb. per sec. 0.0035 lb. water evap. per hr. from and at 212°F. 44.254 ft.-lb. per min.
1 Watt per sq. in. =	8.20 Btu. per sq. ft. per min. 6373 ft.-lb. per sq. ft. per min. 0.1931 hp. per sq. ft.
1 Btu. =	1054.2 watt-sec. 777.54 ft.-lb. 107.5 kg.-meters 0.0002928 kw.-hr. 0.0003927 hp.-hr. 0.0000685 lb. carbon oxidized with perfect efficiency 0.001030 lb. water evap. from and at 212°F.
1 Btu. per sq. ft. per min. =	0.1220 watt per sq. in. 0.01757 kw. per sq. ft. 0.02356 hp. per sq. ft.
1 Kilogram-meter =	7.233 ft.-lb. 0.000003653 hp.-hr. 0.000002724 kw.-hr. 0.009302 Btu.
1 Lb. carbon oxidized with perfect efficiency =	14,600 Btu. 1.11 lb. anthracite oxidized 2.5 lb. dry wood oxidized 22 cu. ft. illuminating gas oxidized 4.26 kw.-hr. 5.733 hp.-hr. 11,352,000 ft.-lb. 15.05 lb. of water evap. from and at 212°F.
1 Lb. water evaporated from and at 212°F. =	0.2841 kw.-hr. 0.3811 hp.-hr. 970.4 Btu. 104,320 kg.-meter 1,023,000 joules 754,525 ft.-lb. 0.066466 lb. carbon oxidized with perfect efficiency

TABLE 14

WEIGHTS AND MEASURES

Length

1 mil = 0.001 in.
1 in. = 2.54 cm. = 25.4 mm.
1 link = 7.92 in. = 20.12 cm.
12 in. = 1 ft. = 0.30479 meter = 30.5 cm.
3 ft. = 1 yd. = 0.91437 meter = 36 in.
5½ yd. = 1 rod or pole = 16½ ft. = 198 in.
22 yd. = 1 chain = 4 rods = 66 ft. = 100 links
40 rods = 1 furlong = 220 yd. = 660 ft. = 10 chains
8 furlongs = 1 statute or land mile = 320 rods = 1760 yd.
5280 ft. = 1 statute or land mile = 1.609 kilometers
1 geographical or nautical mile = 1 min. = 1/60 deg.
1 nautical mile, British standard = 6080 ft.
1 nautical mile = 1.115 statute or land miles
1 statute or land mile = 0.869 nautical mile
3 nautical miles = 1 league

Square Measure

1 sq. yd. = 9 sq. ft. = 0.836 sq. meter
1 sq. ft. = 114 sq. in. = 920 sq. cm.
1 sq. in. = 6.4514 sq. cm.
A section of land is 1 mile square = 640 acres
1 acre = 43,560 sq. ft. = 0.40467 hectare
1 sq. acre = 208.71 ft. on each side

Cubic Measure

1 cu. yd. = 27 cu. ft. = 7645 cu. meters
1 cu. yd. = 201.97 (wine) gal. = 7.645 hectoliters
1 cu. ft. = 1728 cu. in. = 28,315.3 cu. cm.
1 cu. ft. = 7.4805 (wine) gal. = 28.315 liters
1 cu. ft. = 6.2355 imperial gal.
1 cord of wood = 128 cu. ft., being 4 x 4 x 8 ft.
1 perch of stone = 24¾ cu. ft., being 16½ x 1½ x 1 ft., generally taken as 25 cu. ft.

Liquid Measure

1 gill = ¼ pt. = 7.22 cu. in. = 4 fl. oz.
1 pt. = 28.88 cu. in. = 16 fl. oz.
2 pt. = 1 qt. = 57.75 cu. in. = 0.9463 liter
4 qt. = 1 gal. = 231 cu. in. = 3.7852 liters
1 imperial gal. = 277.463 cu. in. = 4.8045 qt.

Dry Measure

1 std. U.S. bu. = 2150.42 cu. in.
1 std. U.S. bu. = 4 peck
1 peck = 2 gal. = 8 qt.
1 gal. = 4 qt. = 268.8 cu. in.
1 qt. = 2 pt. = 67.2 cu. in.
100 bu. = 124.5 cu. ft. (approximately)
80 bu. = 100 cu. ft. (approximately)

Avoirdupois Weight

1 lb. = 16 oz. = 7000 grains = 0.45359 kg. = 453.59 gm.
1 ton = 2240 lb. A short ton = 2000 lb.
A fluid ounce is a measure of capacity and means in the American system 1/16 pint wine measure.
1 fl. oz. = 1.042 oz. avoirdupois
1 fl. oz. = 455.6 grains of distilled water
1 fl. oz. = 29.52 cu. cm.
In England a fluid ounce means 1/20 imperial pint = 1 imperial ounce = 437.5 grains of distilled water = 28.35 cu. cm.
1 metric ton = 1000 kg. = 2205 lb.

Troy Weight

1 lb.[a] = 12 oz. = 5760 grains = 0.37324 kg.
1 oz. = 20 pennyweights = 1.0971 oz. avoirdupois
1 pennyweight = 24 grains
1 karat used in weighing diamonds = 3.168 grains = 0.205 gm.

Apothecaries' Weight

1 lb.[a] = 1 lb. troy weight = 12 oz.
1 oz.[a] = 8 drachms
1 drachm = 3 scruples
1 scruple = 20 grains

[a] The pound and ounce are the same in apothecaries' as in troy weight. One ounce avoirdupois is 437.5 grains, and 1 ounce troy is 480 grains, but 1 grain has the same value in troy, apothecaries' and avoirdupois and is equal to 0.0648 gm. in the metric system.

TABLE 15
FORCE CONVERSION FACTORS

FORCES OR WEIGHTS PER UNITS OF LENGTH (LINEAR WEIGHTS)

1 dyne per centimeter = 0.00101979 gm./cm. = 0.000183719 poundal/in.
1 gram per centimeter = 980.5966 dynes/cm. = 0.180154 poundal/in.
1 poundal per inch = 5443.11 dynes/cm. = 5.55081 gm./cm. = 0.0310832 pound/in.

Grams per Centimeter, Gm./Cm.	Grains per Inch, Gr./In.	Pounds per Inch, Lb./In.	Pounds per Foot, Lb./Ft.	Pounds per Yard, Lb./Yd.	Kilograms per Meter, Kg./M.	Short Tons, (2000 Lb.), per Mile	Gross Tons, (2240 Lb.), per Mile	Metric Tons, (1000 Kg.), per Kilometer
1	39.1983	$0.^{2}_{0}5600$	0.06720	0.20159	0.10	0.17740	0.15839	0.10
0.02551	1	$0.^{3}_{0}1429$	$0.^{2}_{0}1714$	$0.^{2}_{0}5143$	$0.^{2}_{0}2551$	$0.^{2}_{0}4526$	$0.^{2}_{0}4041$	$0.^{2}_{0}2551$
178.579	7000	1	12	36	17.8579	31.6800	28.2857	17.8579
14.8816	583.333	0.08333	1	3	1.48816	2.64000	2.35714	1.48816

FORCES OR WEIGHTS PER UNITS OF AREA (PRESSURE)

1 dyne per square centimeter = 0.00101979 gm./cm.^{2} = 0.000366646 poundals/in.^{2}
1 gram per square centimeter = 980.5966 dynes/cm.^{2} = 0.457592 poundals/in.^{2}
1 poundal per square inch = 2142.95 dynes/cm.^{2} = 2.18536 gm./cm.^{2} = 0.0310832 pound/in.^{2}

Kilograms per Square Centimeter, Kg./Cm.^{2}	Pounds per Square Inch, Lb./In.^{2}	Pounds per Square Foot, Lb./Ft.^{2}	Short Tons, (2000 Lb.), per Square Foot	Atmospheres, Standard, 760 Mm.	Columns of Mercury (Hg) 13.59593 Sp. Gr.		Columns of Water, Max. Density 4°C.	
					Millimeters	Inches	Meters	Feet
1	14.2234	2048.17	1.02408	0.96778	735.514	28.9572	10	32.8083
0.07031	1	144	0.07200	0.06804	51.7116	2.03588	0.70307	2.30665
$0.^{3}_{0}4882$	$0.^{2}_{0}6944$	1	0.00050	$0.^{3}_{0}4725$	0.35911	0.01414	$0.^{2}_{0}4882$	0.01602

FORCES OR WEIGHTS PER UNITS OF VOLUME (DENSITY)

1 dyne per cubic centimeter = 0.00101979 gm./cm.^{3} = 0.00118528 poundals/in.^{3}
1 gram per cubic centimeter = 980.5966 dynes/cm.^{3} = 1.162283 poundals/in.^{3}
1 poundal per cubic inch = 843.683 dynes/cm.^{3} = 0.860378 gm./cm.^{3} = 0.0310832 pound/in.^{3}

Grams per Cubic Centimeter, Gm./Cm.^{3}	Pounds per Cubic Inch, Lb./In.^{3}	Pounds per Cubic Foot, Lb./Ft.^{3}	Pounds per Cubic Yard, Lb./Yd.^{3}	Kilograms per Cubic Meter, Kg./M.^{3}	Pounds per Bushel, U.S.	Pounds per Gallon, Dry, U.S.	Pounds per Gallon, Liquid, U.S.	Kilograms per Hectoliter, Kg./Hl.
1	0.03613	62.4283	1685.56	1000	77.6893	9.71116	8.34545	100
27.6797	1	1728	46656	27679.7	2150.42	268.803	231	2767.97
0.01602	$0.^{3}_{0}5787$	1	27	16.0184	1.24446	0.15556	0.13368	1.60184

Notations $^{2}_{0}$, $^{3}_{0}$, $^{4}_{0}$, etc., indicate that the $^{2}_{0}$, $^{3}_{0}$, $^{4}_{0}$, etc., are to be replaced by 2, 3, 4, etc., ciphers.
EXAMPLE: 1 kg./m.^{3} = $0.^{4}_{0}3613$ = 0.00003613 lb./in.^{3}

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